

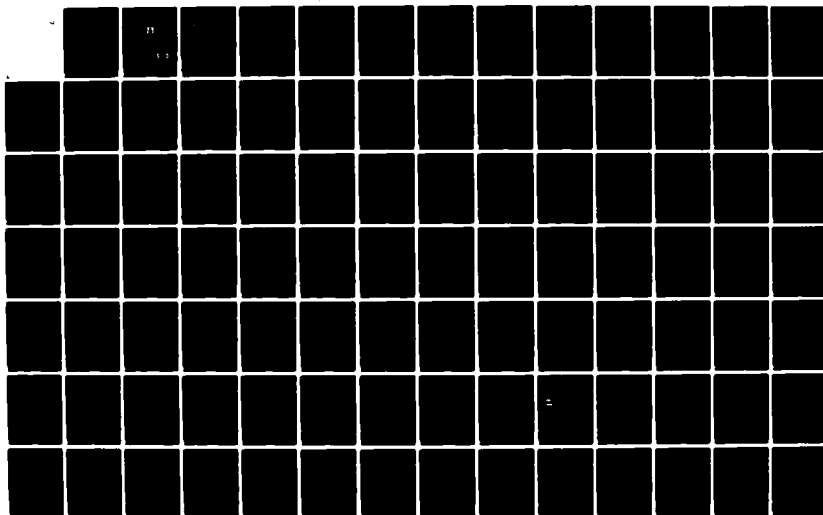
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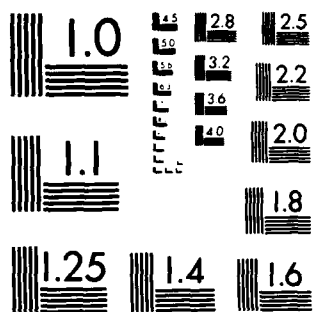
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FOREIGN TECHNOLOGY DIV WRIGHT-PATTERSON AFB OH  
G A GORYACHEVA ET AL. 24 MAY 84 FTD-ID(RS)T-1676-83

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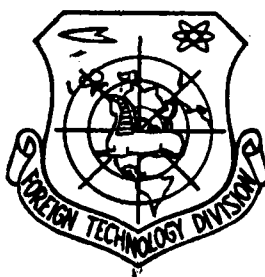
## FOREIGN TECHNOLOGY DIVISION



ACTION OF PENETRATING RADIATION ON RADIO PARTS

by

G. A. Goryacheva, A. A. Shapkin, L. G. Shirshv



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# U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

Block	Italic	Transliteration	Block	Italic	Transliteration
А а	<b><i>А а</i></b>	A, a	Р р	<b><i>Р р</i></b>	R, r
Б б	<b><i>Б б</i></b>	B, b	С с	<b><i>С с</i></b>	S, s
В в	<b><i>В в</i></b>	V, v	Т т	<b><i>Т т</i></b>	T, t
Г г	<b><i>Г г</i></b>	G, g	У у	<b><i>У у</i></b>	U, u
Д д	<b><i>Д д</i></b>	D, d	Ф ф	<b><i>Ф ф</i></b>	F, f
Е е	<b><i>Е е</i></b>	Ye, ye; E, e*	Х х	<b><i>Х х</i></b>	Kh, kh
Ж ж	<b><i>Ж ж</i></b>	Zh, zh	Ц ц	<b><i>Ц ц</i></b>	Ts, ts
З з	<b><i>З з</i></b>	Z, z	Ч ч	<b><i>Ч ч</i></b>	Ch, ch
И и	<b><i>И и</i></b>	I, i	Ш ш	<b><i>Ш ш</i></b>	Sh, sh
Й й	<b><i>Й й</i></b>	Y, y	Щ щ	<b><i>Щ щ</i></b>	Shch, shch
К к	<b><i>К к</i></b>	K, k	Ъ ъ	<b><i>Ъ ъ</i></b>	"
Л л	<b><i>Л л</i></b>	L, l	Ы ы	<b><i>Ы ы</i></b>	Y, y
М м	<b><i>М м</i></b>	M, m	Ь ь	<b><i>Ь ь</i></b>	'
Н н	<b><i>Н н</i></b>	N, n	Э э	<b><i>Э э</i></b>	E, e
О о	<b><i>О о</i></b>	O, o	Ю ю	<b><i>Ю ю</i></b>	Yu, yu
П п	<b><i>П п</i></b>	P, p	Я я	<b><i>Я я</i></b>	Ya, ya

\*ye initially, after vowels, and after ъ, ы; e elsewhere.  
When written as ё in Russian, transliterate as yë or ë.

## RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	sinh <sup>-1</sup>
cos	cos	ch	cosh	arc ch	cosh <sup>-1</sup>
tg	tan	th	tanh	arc th	tanh <sup>-1</sup>
ctg	cot	cth	coth	arc cth	coth <sup>-1</sup>
sec	sec	sch	sech	arc sch	sech <sup>-1</sup>
cosec	csc	csch	csch	arc csch	csch <sup>-1</sup>

## Russian English

rot curl  
lg log

## GRAPHICS DISCLAIMER

All figures, graphics, tables, equations, etc. merged into this translation were extracted from the best quality copy available.

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PAGE 1

ACTION OF PENETRATING RADIATION ON RADIO PARTS. .

G. A. Goryacheva, A. A. Shapkin, L. G. Shirshev.

In the book is examined the effect of the ionizing radiations/emissions on the electrophysical characteristics of the materials, utilized for producing the radio parts. Primary attention is paid to the theoretical and experimental investigations of the character of a change of the parameters of materials in the conditions for pulse and continuous  $\gamma$ - and neutron radiations/emissions.

Are given the results of investigations on the reversible and irreversible disturbances/breakdowns of the electrophysical and operating parameters of different types of resistors and capacitors in the process and after effect on them of  $\gamma$ - and neutron radiations/emissions. The fundamental procedures of the measurement of the parameters of radio parts under radiation conditions are given.

Page 3.

Preface.

The need for the creation of different materials, articles and radio-electronic equipment, reliably working in the fields ionizing radiations/emissions appeared with the expansion of the field of application of nuclear radiation. It was explained as a result of experimental investigations that radio-electronic equipment and its completing elements/cells were sensitive to the effect of different forms of radiation. This it determines and, unfortunately, frequently limits the use/application of many electronic and automatic systems in the constructions/designs of nuclear reactors and on the objects, which can prove to be in the zone of action of penetrating radiation.

The mass elements/cells include the radio parts (resistors and capacitors), which comprise more than half of all elements/cells of contemporary radio-electronic equipment. Consequently, from the radiation durability of radio parts, i.e., from their ability to retain the characteristics and the parameters within the limits of the established/installed norms during and after the effect of the ionizing radiations/emissions, depends the reliability of the work of radio-electronic equipment. The fundamental operating factors, which

determine the reliability of the operation of radio parts under the normal conditions, are: electrical load, temperature, environment and mechanical loads. During the effect of the ionizing radiations/emissions these factors include also the form of radiation/emission, its intensity and duration of irradiation.

The processes, which occur under the effect of the ionizing radiations/emissions, can directly cause changes in the electrophysical and operating characteristics of radio parts or "wake up" the physicochemical processes in the structural materials, which cause as a result a change in the properties of capacitors and resistors.

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In turn, changes in the characteristics of radio parts can lead under specific conditions to temporary or permanent changes in the parameters of equipment. The cases of short duration failures or failures of equipment as a result of a change of the parameters of radio parts in the conditions of the effect of the ionizing radiations/emissions are possible.

To the study of the problems of the effect of pulse and prolonged  $\gamma$ - and neutron radiations/emissions on the resistors and

the capacitors is dedicated this book. This information, in the opinion of the authors, can prove to be useful for the engineers and scientific workers, who work in the field of application and engineering the radio parts, and also for the instructors and the students of schools of higher education of the corresponding types.

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Chapter 1.

Character of interaction of  $\gamma$ - and neutron radiations/emissions with the materials, utilized in the constructions/designs of radio parts.

### 1.1. Radiation effects in the materials.

Character and degree of a change in the electrophysical properties of radio parts depend, first of all, on the reaction of the materials, from which they are prepared, to the effect of the ionizing radiations/emissions, and also from the design features of articles and from the environment. Therefore the description of the processes, which take place in the radio parts under the effect of  $\gamma$ - and neutron radiations/emissions, should be begun from the examination of the character of the interaction of different forms of radiation/emission with the materials, entering the construction/design of radio parts, and with the environment.

Neutrons and  $\gamma$ -quanta, passing through the substance, interact either with the atomic nuclei or with the orbit electrons. As a result of direct (primary) interaction of radiation/emission with the

atoms of substance can occur the atomic displacement from the lattice points, the excitation of electrons, atoms and molecules and nuclear conversions. Collision interaction atoms and electrons, causing cascade type secondary processes, produce further ionization and disturbance/breakdown of structure of substance. One and the same laws control primary and secondary processes. Character and degree of the disturbances/breakdowns, which appear in the substances, depend on energy spectrum of  $\gamma$ - and neutron radiations/emissions.

Penetrating radiation<sup>1</sup> during the nuclear and thermonuclear blasts and from the nuclear energy and power plants contains in its spectrum of  $\gamma$ -quantum with the kinetic energy to 10 MeV and neutrons with the energy to 14 MeV.

FOOTNOTE <sup>1</sup>. By penetrating radiation, or penetrating radiation/emission, it is accepted to understand neutron and  $\gamma$ -radiation, which is formed as a result of fission reactions and synthesis during the nuclear explosions and in nuclear reactors.  
ENDFOOTNOTE.

Radiation effects during the gamma-irradiation. For  $\gamma$ -quanta with the kinetic energy to 10 MeV are characteristic three fundamental processes of interaction of  $\gamma$ -radiation with the substance: photoelectric absorption (photoelectric effect), Compton

effect (Compton effect) and the effect of pair formation.

In the radio engineering materials during the photoelectric absorption basic part of the energy of the falling/incident (affecting)  $\gamma$ -radiation passes into the energy of photoelectrons.

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During the Compton effect of  $\gamma$ -quanta the part of its energy loses and is changed direction of motion. Energy the  $\gamma$ -quantum, transmitted to electron, is expended/consumed on the electron detachment from the atom and the communication/report to it of kinetic energy. That deflected from its initial motion (scattered) of  $\gamma$ -quanta interacts with the electron of another atom, etc. The quantum energy decreases as a result of repeated collisions and occurs the effect of photoelectric absorption.

As a result of interaction the  $\gamma$ -quantum with coulomb field of atomic nucleus occurs the formation of the pair of particles the electron - positron. This process is called the effect of the formation of electron-positron pairs. Pair formation can occur during the absorption  $\gamma$ -quantum with the energy, greater than total rest energy of electron and positron (more than the doubled rest energy of electron, equal to  $2m_0c^2=1.02$  MeV). Positron (unstable elementary

particle) in turn interacts with the electron of medium, which leads to the formation of two quanta of annihilation radiation/emission.

Thus, with the passage of  $\gamma$ -quanta through the substance they either are absorbed or they are scattered. The total cross section of weakening  $\gamma$ -radiation is equal to the sum of the sections of photoelectric effect, Compton effect and effect of pair formation.

A number of quanta, which left (absorbed) from the parallel flow of  $\gamma$ -quanta with the passage of the layer of substance, is equal [to 1]

$$d\Phi_\gamma = -\Phi_\gamma \sigma n dx = -\Phi_\gamma \mu dx = -\Phi_\gamma \frac{\mu}{\rho} d\left(\frac{\rho}{\rho}\right) = -\Phi_\gamma \frac{dx}{\lambda}, \quad (1.1)$$

where  $\Phi$  - flow of  $\gamma$ -quanta, quanta/cm<sup>2</sup>; dx - thickness of the layer of substance, through which is passed the normally incident flux of  $\gamma$ -quanta, cm;  $\sigma$  - total interaction cross section, designed for one atom, cm<sup>2</sup>; n - number of atoms in 1 cm<sup>3</sup> of substance;  $\rho$  - density of medium, g/cm<sup>3</sup>; dm - mass of substance in layer with an area of 1 cm<sup>2</sup> and by thickness dx, g/cm<sup>2</sup>;  $\mu = \sigma n$  - linear coefficient of absorption of  $\gamma$ -radiation, cm<sup>-1</sup>;  $\mu_{\text{mac}} = \mu/\rho$  - mass coefficient of absorption of  $\gamma$ -radiation, cm<sup>2</sup>/g;  $\lambda = 1/\mu$  - mean free path  $\gamma$ -quantum in substance, cm.

The penetration probability of the processes of photoelectric effect, Compton effect and effect of pair formation depends, mainly,

on energy of  $\gamma$ -quanta and atomic number of substance. The regions of the kinetic of energies, in which predominate different processes during interaction of  $\gamma$ -quanta with the substances, which have different atomic number, they are shown in Table 1.1. It follows from these data that with the energy of  $\gamma$ -quanta from 100 keV to 10 MeV in the substances with the atomic number to 40, i.e., almost for all radio engineering materials predominant is the effect of Compton effect.

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Therefore during the practical determination of a number of those left (absorbed) from the general/common/total flow of  $\gamma$ -quanta with the passage of the layer of material it is possible to consider only the effect of Compton effect.

Knowing the sections of the Compton effect of material, it is easy to determine the mass coefficient of absorption of  $\gamma$ -radiation according to the following formula:

$$\mu_{\text{acc}} = \frac{\mu}{\rho} = \sigma N \frac{Z}{A}. \quad (1.2)$$

If the coefficient of absorption of any material is known, then for the majority of other radio engineering materials the linear absorption coefficient is calculated from the expression

$$\mu = \mu_0 \frac{\rho}{\rho_0} \quad (1.3)$$

In formulas (1.2) and (1.3)  $N$  - Avogadro number;  $A$  - mass number;  $\mu$  and  $\mu_0$  - linear coefficients of absorption of the determined and known substance respectively;  $\rho$  and  $\rho_0$  - substance density with  $\mu$  and  $\mu_0$  respectively.

The degree of accuracy of expression (1.3) is determined by constant proportions  $Z/A$  upon transfer from one substance to another. For the majority of light substances value  $Z/A=0.5$ , with exception of hydrogen ( $Z/A=1$ ), where  $Z$  - the atomic number of substance. It follows from formula (1.3) that the mass absorption coefficients for the majority of radio engineering materials are identical. Consequently, in one gram of substance (for example, air, iron, aluminum, polyethylene, etc.) is absorbed in the first approximation, the identical energy content of  $\gamma$ -radiation. Quantities of absorbed energy can be determined according to the formula

$$\Delta E = \mu_{\text{mass}} \Phi_{\gamma} E_{\gamma} \quad (1.4)$$

where  $\Phi_{\gamma}$ ,  $E_{\gamma}$  - flow and energy of  $\gamma$ -quanta respectively.

Table 1.1. The value of quantum energy, with which in the weakening predominates one of three processes of interaction the  $\gamma$ -quantum with the element/cell.

(1) Вещество	(2) Фотоэффект, кэВ	(3) Комптон-эффект, Мэв	(4) Эффект образования пар, Мэв
Воздух (5)	< 20	$0.03 < E_{\gamma} < 23$	> 23
Алюминий (6)	< 50	$0.05 < E_{\gamma} < 15$	> 15
Железо (7)	< 120	$0.12 < E_{\gamma} < 10$	> 10
Свинец (8)	< 500	$0.5 < E_{\gamma} < 5$	> 5

Key: (1). Substance. (2). Photoelectric effect, keV. (3). Compton effect, MeV. (4). Effect of formation of pairs, MeV. (5). Air. (6). Aluminum. (7). Iron. (8). Lead.

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Energy of  $\gamma$ -radiation, which is absorbed per unit of volume of substance, can be determined also according to formula (1.4), but only instead of the mass absorption coefficient it is necessary to utilize a linear coefficient of absorption (Table 1.2).

Energy, absorbed by substance under the influence on it of the flow of  $\gamma$ - quanta, with the kinetic energy to 10 MeV, is broken up in essence to the processes of ionization and atom excitation and molecules.

The rate of formation of free ions and electrons in the substance depends on the radiation dose rate. The more the energy it is absorbed by substance per unit time, the more it proceeds the electron detachments from the atom and, therefore, the above becomes the concentration of free charge carriers in the material. An increase in the concentration of free charge carriers is the fundamental reason for an increase in the conductivity of electrical insulating materials.

Radiation effects during the neutron irradiation. If as a result of primary interaction of  $\gamma$ -radiation with the substance occur, in essence, the processes of ionization and atom excitation and molecules of elements/cells, then during the neutron irradiation the processes of the damage of the structure of substance predominate.

In contrast to  $\gamma$ -quanta, which interact with the electrons of atoms, the neutrons interact with the atomic nuclei of substance, causing: a) the elastic scattering, which is accompanied by the nucleation of efficiency, by the loss of the part of the kinetic energy and by divergence from the initial direction of the motion of the falling/incident neutron; b) the absorption (capture) of neutrons with the formation of compound nucleus, which is accompanied by the

processes of neutron emission (elastic and inelastic scattering),  $\gamma$ -quanta, protons,  $\alpha$ -particles or by the formation/education of fission fragments.

Table 1.2. Linear coefficient of the energy absorption of  $\gamma$ -quanta by some substances,  $\mu$ ,  $\text{cm}^{-1}$ .

(1) Кинетическая энергия $\gamma$ -кван- та, Мэв	(2) Воздух, $10^{-3}$	(3) Вода	(4) Алюминий	(5) Железо
0,1	0,197	0,171	0,457	2,88
0,2	0,159	0,137	0,325	1,14
0,3	0,138	0,119	0,281	0,857
0,4	0,124	0,106	0,250	0,733
0,5	0,112	0,0967	0,228	0,655
0,6	0,104	0,0894	0,210	0,600
0,8	0,0915	0,0786	0,184	0,521
1,0	0,0818	0,0706	0,166	0,467
1,5	0,0664	0,0576	0,135	0,378
2,0	0,0561	0,0493	0,116	0,329
3,0	0,0452	0,0396	0,0953	0,280
4,0	0,0393	0,0339	0,0837	0,258
5,0	0,0348	0,0302	0,0767	0,245
6,0	0,0316	0,0277	0,0718	0,238
8,0	0,0284	0,0242	0,0656	0,232
10,0	0,0258	0,0221	0,0627	0,234

Key: (1). Kinetic energy is  $\gamma$ -quantum, MeV. (2). Air,  $10^{-3}$ . (3). Water. (4). Aluminum. (5). Iron.

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The effect of ionization is most characteristic for the neutrons with the high kinetic energy. In the energy radiation spectrum of nuclear explosions, and also in the impulse and static reactors such neutrons comprise high portion of the general/common/total neutron flux. Therefore these processes of ionization should be considered in the calculations. As an example Fig. 1.1 gives the typical neutron flux densities of different energies for thermonuclear blast [2].

Fission neutrons and delayed neutrons, emitted by nuclear energy and power plants, have a spectrum of kinetic energies from the thermal (0.025 eV) to several mega-electron-volts. Usually the neutron spectrum of fission reaction over the ranges of kinetic energies is subdivided into the following three groups:

- 1) slow - with the kinetic energy from zero to  $1 \cdot 10^3$  eV (here enter also thermal neutrons);
- 2) intermediate - with the energy from  $1 \cdot 10^3$  to  $0.1 \cdot 10^6$  eV (0.1 MeV);
- 3) rapid - with the energy of more than 0.1 MeV (100 keV).

The probability of the processes of interaction of neutrons with the atomic nuclei of elements/cells depends, mainly, on neutron energy and nature of target nuclei. This probability they quantitatively characterize with complete effective interaction cross section

$$\sigma = \sigma_s + \sigma'_s + \sigma_a, \quad (1.5)$$

where  $\sigma_a = \sigma_f + \sigma_p + \sigma_a + \sigma_j + \dots$ ;  $\sigma$  - complete effective interaction cross section of neutrons with the nuclei of this substance;  $\sigma_s$  and  $\sigma'_s$  - section of elastic and inelastic scattering respectively;  $\sigma_a$  - reaction cross-section, as a result of which the neutrons are

absorbed and occur the processes of emitting of  $\gamma$ -quanta ( $\sigma_\gamma$  - radiation-capture cross section), of protons ( $\sigma_p$ ),  $\alpha$ -particles ( $\sigma_\alpha$ ) and fission reaction of nuclei ( $\sigma_f$ ).



Fig. 1.1. Typical distribution in the time of the neutron flux density of different energy during the thermonuclear blast.

Key: (1). Neutron flux density neutron( $\text{cm}^2 \cdot \text{s}$ ). (2). MeV. (3). Time after blast,  $\mu\text{s}$ .

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With the kinetic neutron energy to 14 MeV the processes of elastic scattering are most effective.

For the fast and intermediate neutrons (with the kinetic energy from 0.05 to 14 MeV) the elastic scattering is the fundamental process of interaction with the substance. The probability of capturing the fast neutrons is into hundreds of times less than the probability of scattering. Only capture reactions of neutrons, accompanied by heat liberation, are most probable for some light nuclei (lithium, boron, helium and nitrogen) during interaction with

the intermediate neutrons.

The probability of inelastic scattering is insignificant, since this scattering can occur only during irradiation of substances by neutrons with the energy of more than energy of the first excitation level of nucleus. Thus, for the light nuclei the first excitation levels have energy on the order of 0.5-5 MeV. Reactions with the emission of the charged/loading elementary particles are possible for the neutrons with the energy, which exceeds the specific threshold value (as a rule, more than 1 MeV). This energy is necessary for overcoming with the charged/loading particle of potential Coulomb barrier with its escape from the excited nucleus.

Radiation capture is characteristic for the slow and especially thermal (with the energy 0.025 eV) neutrons. But for the majority of substance the effective capture cross-sections of slow neutrons several times of less than effective scattering cross sections. And finally, reactions throated of several particles (neutrons, protons, alpha particles, etc.) are possible during the bombardment of the atomic nuclei of substances with neutrons with the energy of more than 20 MeV.

Thus, the materials, utilized in the constructions/designs of radio parts, according to the character of interaction with the

neutrons can be divided into two groups.

1. Basic group - nonfissionable substances, on which operate in essence fast neutrons, since effective capture cross-sections of slow neutrons in them are insignificant in comparison with interaction cross sections of fast neutrons. The action of slow neutrons during the practical evaluation of the radiation durability of these materials can be disregarded/neglected [3].

2. Materials, which possess large effective capture cross-section of thermal neutrons (containing boron, silver, zloty, indium, etc.). Are especially dangerous these processes for the materials, whose properties depend substantially on the content of a small quantity of foreign atoms, for example donors or electron acceptors. However, in the majority of the cases during irradiation in the reactor a number of the displaced atoms, which also can be donors, acceptors, traps of electrons, is considerably more than a number of nuclear conversions.

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Consequently, under the influence of neutron radiation/emission fundamental primary processes in the radio-materials - processes of atomic displacement in crystal lattice.

As a result of interaction of neutrons with the substance, as already mentioned, the product nuclei of efficiency, the charged/loaded particles, the  $\gamma$ -quanta and scattered neutrons, which interact both with the nuclei and with the electrons of atoms. These processes can lead to the damage of the structure of substance, and also to the ionization of substance.

As a result of atomic displacement in crystal lattice of substance can appear the vacant sites, interstitial atoms, substituted atoms, thermal (heat) peaks and peaks of shift [3-6].

A quantity of displaced atoms per unit of volume of solid can be determined according to the formula

$$N_d = \Phi(E) n_0 \sigma(E) \bar{\nu},$$

where  $N_d$  - number of displaced atoms per unit of volume;  $\Phi(E)$  - the flow of the interacting particles with energy  $E$ ;  $\bar{\nu}$  - average number of displaced atoms, in reference to one primary displaced atom;  $n_0$  - number of atoms per unit of volume of substance.

A number of displaced atoms in the substance depends on kinetic energy of the falling/incident neutrons. In accordance with the theory of Kinchin and Piz Fig. 1.2 gives the expected curves of the

dependence of a number of generatrices of shifts  $\delta$  on the value of energy of neutron [7]. It is evident from these dependences that a number of shifts especially grows/rises with the neutron energy on the order of 0.1 MeV and more. Therefore during the evaluation of the radiation durability of radio parts usually consider neutron fluxes with the energy more than 0.1 MeV [3].

#### 1.2. Secondary processes in the materials.

Physicochemical processes proceed as a result of ionization and damage of structure in the materials. Character and rate of the course of these processes depend on the neutron flux density and rate of the dose of  $\gamma$ -radiation, exposure time, properties of the irradiated substance and operating conditions (the environment, temperature, humidity, load, etc.).

The fundamental physicochemical processes in the materials, which change operating characteristics of radio parts, are radiation heating, chemical processes in the materials (structuring and destruction in the polymers, oxidation, etc.), and also other processes, which call changes in the structure of materials.

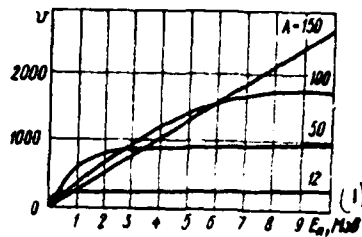


Fig. 1.2. Dependence of a number of shifts in the substance on the kinetic energy of the falling/incident neutrons.

Key: (1). MeV.

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Heating effect of  $\gamma$ - and neutron radiations/emissions. As a result of the effect of the ionizing radiations/emissions the large part of the energy absorbed in the material as the final result is converted into the heat. This energy is expended/consumed on the heating or as it is accepted to speak, to the radiation heating.

The degree of the heating (temperature) of material or article depends on the following fundamental factors: the neutron flux density and  $\gamma$ -quanta (dose rate) and duration of their effect; form and material density; the sizes/dimensions of article; the thermal conductivity of material; the ambient temperature; heat-transfer conditions from the surface of article in the environment (emission,

convection of heat); the transfer of heat (thermal conductivity) by means of the contact contacts (conclusions/outputs, coupling) to other materials and to the articles, utilized in the equipment.

Gamma quantum and fast neutrons as a result of the high penetrating power cause heat liberation throughout entire space. The gradients of temperature, which lead to the thermal stresses between different elements/cells and layers of articles, appear by virtue of the possible nonuniformity of radiation heating. Consequently, radiation heating - complex function of the enumerated factors can be unambiguously determined only for the limited conditions.

In the absence of heat emission into the environment entire/all absorbed energy, being converted into heat, will go to an increase in the temperature of material or article

$$\Delta E = \Delta Q = C_m m \Delta T, \quad (1.6)$$

where  $\Delta Q$  - quantity of heat in the joules, transmitted to the heat-insulated body;  $\Delta T = T_2 - T_1$  - increase in the temperature of material, deg;  $C_m$  - specific heat of material, J/g;  $m$  - mass of body, g.

Under the normal conditions for operation the quantity of thermal energy, which is expended/consumed in the article on its heating, can be determined from the expression

$$\Delta q = C_m m \Delta T - \alpha S \Delta T,$$

where  $\alpha = \alpha_r + \alpha_c$  - heat-transfer coefficient,  $W/(cm^2 \cdot deg)$ ;  $\alpha_r$  - radiant heat-transfer coefficient,  $W/(cm^2 \cdot deg)$ ;  $\alpha_c$  - convective heat-transfer coefficient,  $W/(cm^2 \cdot deg)$ ;  $S$  - surface area of article.

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For the heat-insulated body a quantity of thermal energy, isolated as a result of acting the neutrons, can be determined according to the formula

$$\Delta Q = K_n \Phi_n V = K_n \Phi_n \frac{m}{\rho}, \quad (1.7)$$

where  $V$  - space of material;  $K_n$  - coefficient of heat release in the material for the neutron flux of this energy spectrum;  $\Phi_n$  - neutron flux.

With the aid of equation (1.7) it is possible to also determine thermal energy during the absorption of  $\gamma$ -radiation in the substance, if the coefficient of heat release for  $\gamma$ -quanta is known.  <sup>$\Phi_\gamma$</sup>  Usually we deal concerning the simultaneous effect of  $\gamma$ - and neutron radiations/emissions; therefore general/common/total energy of heat release in the article can be calculated according to the formula

$$\Delta Q = \sum_{i=1}^n K_{\gamma, i} \frac{m_i}{\rho_i} \Phi_{\gamma, i} + \sum_{i=1}^n K_{n, i} \frac{m_i}{\rho_i} \Phi_{n, i} \quad (1.8)$$

where  $n$  - number of materials, entering the article. In formula (1.8) the first member in the right side of the equality considers heat release due to the absorption of  $\gamma$ -radiation. The coefficient of heat release for this form of the ionizing radiation/emission (with the specific energy) depends in essence on nature of the irradiated material.

If one considers that in the presence of the reactions of nuclear fission and synthesis fast neutron flux is considerable (in several dozen times) the flow of  $\gamma$ -quanta is less, and the interaction cross sections of neutrons and  $\gamma$ -quanta for the elements/cells with an atomic weight are more than nine - one order, then it becomes obvious, that the heat release in such elements/cells is caused in essence by  $\gamma$ -radiation.

Exception/elimination from this position comprise: a) hydrogenous substances, in which the section of interaction with the fast neutrons is more interaction cross section with the  $\gamma$ -quanta. Therefore for hydrogenous substances heat release is caused by interaction both with the fast neutrons and with the  $\gamma$ -quanta; b) the substances, which possess the large capture cross section of thermal neutrons - boron, cobalt, manganese and others.

The radiation heating of materials and radio parts is made with

the more rigid conditions of their work, causing the supplementary reversible changes of the parameters, and in a number of cases and the irreversible changes in both the parameters and the operating characteristics.

Chemical processes. The processes of ionization and damage of the structure of materials can be the reason for the course of chemical reactions. Substantial changes occur in the organic polymeric materials, in which as a result of irradiation the covalent bonds easily break down themselves and free radicals are formed.

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In this respect they differ from metals and ceramic materials, which are characterized by crystal structure, usually which does not contain covalent bonds, and their properties under the effect of the ionizing radiations/emissions are changed to a lesser degree. The formed radicals are the initiators of the chemical reactions, which bring as a result to the processes of structuring (to cross linking) and destruction (splitting/fission of molecules). Both processes go simultaneously with predominance of one of them and are accompanied by gas evolution (hydrogen, the small numbers of compounds of light molecular weight, halides and other substances).

Damages in the polymers during irradiation in the first approximation, depend on the total absorbed dose. The schematic diagram of effect of  $\gamma$ - and neutron radiations/emissions on the polymeric materials is given in Fig. 1.3. Aromatic polymers have highest radiation resistance, since aromatic structures because of the resonance character of their properties, contribute to the energy absorption of radiation/emission without a change in the structure of polymer. Their number includes different form the polyphenyls, for example polystyrene.

The course of chemical reactions in the polymers depends also on the content in them of the dissolved gases and composition of the environment. The presence of oxygen, for example, contributes to the formation of the peroxide and hydroperoxide compounds, which can cause the destruction of the polymer chains. During irradiation in air the degree of the effect of oxidation processes depends on the rate of diffusion of oxygen into materials [8].

During the evaluation of the radiation durability of polymeric materials it is necessary to consider that the irradiation leads to the decrease of the degree of the crystallinity of polymers. This can have an essential effect on kinetic processes during the irradiation, on the lifetime and the ability to take part in the radiation chemistry reactions of the initial materials of radiolysis (ions,

electrons).

It is established/installed in works [8, 9], that the crystallizing polymers are capable of accumulating the products of the radiolysis: ions, free radicals. The stability, for example, of free radical depends on the sizes/dimensions of crystal regions, degree of their defectiveness and increases with an increase in the degree of the crystallinity of polymer. Therefore the crystallinity of polymer has an effect on dielectric characteristics, on the mechanism of dielectric losses, polarization and electrical conductivity of material, which is located in the conditions of the effect of radiation.

Fig. 1.4 gives the relative radiation durability of some polymeric materials, most widely used in radio component manufacturing.

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Ionization and atom excitation and molecules in the inorganic substances do not lead to the formation of new connections/communications; therefore as a result of processes of ionization in them do not occur chemical changes.

However, inorganic dielectrics and metals also can interact with the impurities (for example, by oxygen) soluble in them and with the chemically active elements/cells of the environment, which appear under the influence of radiation.

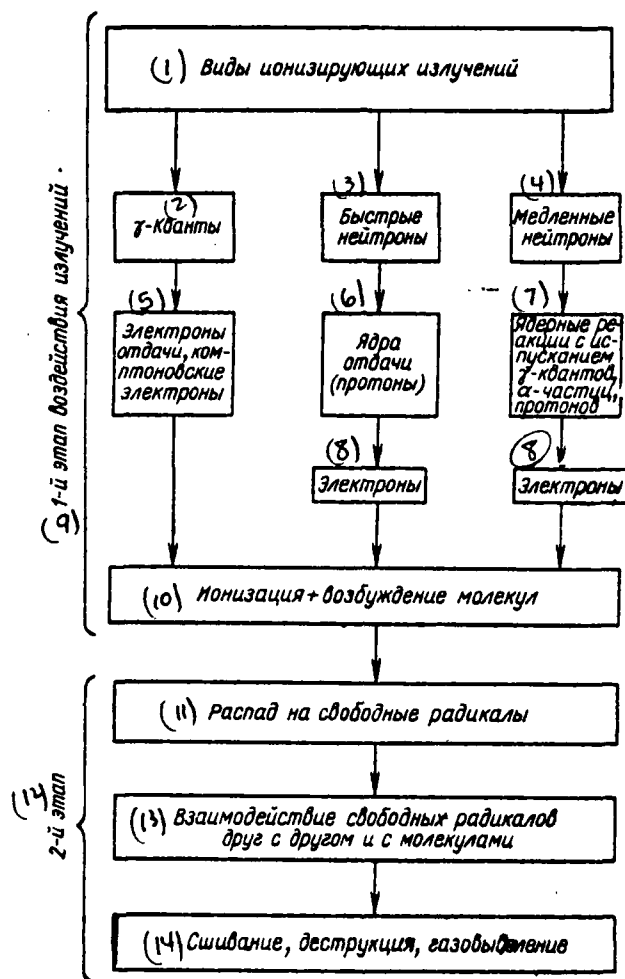


Fig. 1.3. Diagram of effect of  $\gamma$ - and neutron radiations/emissions on the high-molecular organic matter.

Key: (1). Forms of the ionizing radiations/emissions. (2).  $\gamma$ -quantum. (3). Fast neutrons. (4). Slow neutrons. (5). Recoil electrons, Compton electrons. (6). Recoil nuclei (protons). (7). Nuclear

reactions with emission of  $\gamma$ -quanta,  $\alpha$ -particles, protons. (8). Electrons. (9). 1st stage of radiation effect. (10). Ionization + molecular excitation. (11). Decay to free radicals. (12). 2nd stage. (13). Interaction of free radicals with each other and with molecules. (14). Join, destruction, generation of gas.

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If we, for example, irradiate metals and alloys in the presence of gases, liquids or solid bodies, sensitive to the ionization, then chemical reactions on the surface of material can flow/occur/last as a result of the formation of ions and free radicals. Therefore under the appropriate conditions possible to expect the amplification of the reactions of oxidation, nitriding or increase of the rate of corrosion. Thus, when, on the surface of the metals, water is present, continue the processes of corrosion. These processes are caused by formation/education in the water under the radiation effect of the molecules of peroxide of hydrogen and hydrogen, and also radicals H and OH. With the increase of temperature the rate of corrosion during irradiation increases [10].

In the points of connections of low-melting metal (lead, tin, zinc, aluminum) and inorganic substances with the high-molecular compounds, in view of the creation in the latter under the radiation

effect of free radicals, the course of chemical reactions with the formation of organometallic compounds [6] is possible.

The degree of radiation-chemical changes examined in the material can be evaluated only for the specified conditions. As an example Fig. 1.5 shows the ranges of values of the exposure doses of the  $\gamma$ -radiations, in which are developed chemical changes in materials [11].

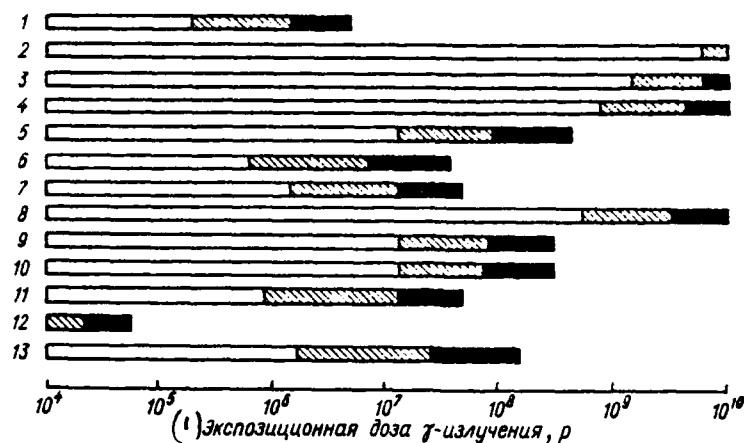


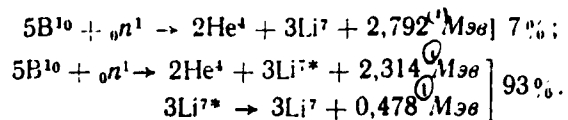
Fig. 1.4. Relative radiation durability of polymeric materials depending on the exposure dose of  $\gamma$ -radiation. Black strips - from moderated to severe damage; shaded - from the weak to the moderate damage. 1 - phenol plastic without the filler; 2 - phenol plastic, glass-reinforced; 3 - epoxy resin with the aromatic hardener; 4 - silicone with the filler from the fiberglass or with the mineral filler; 5 - silicone without the filler; 6 - melamine-formaldehyde resin; 7 - cellulose acetate; 8 - polystyrene; 9 - polyvinyl chloride; 10 - polyethylene; 11 - polytrifluorochloroethylene (polychlorotrifluoroethylene); 12 - teflon (teflon); 13 - natural rubber.

Key: (1). Exposure dose of  $\gamma$ -radiation, R.

Effect of thermal neutrons on the materials. as already mentioned, the effect of thermal neutrons causes the greatest changes in the properties of materials, which contain substances (boron, manganese, cadmium, etc.) with the high value of the capture cross section of these neutrons.

In the radio parts frequently are applied the boron-containing substances, which are included, for example, in the conducting film of resistors, into the composition of the glass, utilized as the foundations or the protective coatings, etc.

Boron possesses the large capture cross section of thermal neutrons ( $\sigma=756.4$  barn). As a result of capturing the thermal neutrons occurs the cleavage reaction of the boron atom, which is accompanied by the formation of the atoms of new elements/cells - lithium Li helium He, and also by isolation/liberation large of energies. Nuclear reaction occurs as follows [12]:



Key: (1). MeV.

The average/mean value of the energy, isolated as a result of

capturing the thermal neutrons by the boron atoms, is 2.35 MeV and is distributed inversely proportional to the masses of the generatrices of particles. Consequently, as a result of the course of the processes indicated occurs a change in the chemical composition of the irradiated substance and its heating. The formed initial materials (nuclei of elements/cells) can, in turn, cause the considerable irreversible changes in the properties of materials and radio parts. The isolated helium gas can cause noticeable "swelling-up", also, in the final analysis the decomposition of article.

As a result of capturing the thermal neutrons the unstable radioactive admixtures/impurities, which are the sources of the ionizing radiations/emissions, are formed. The effect of these radiations/emissions on the radio part it is possible not to consider, since their flows are insignificant and virtually do not affect a change in the parameters of articles.

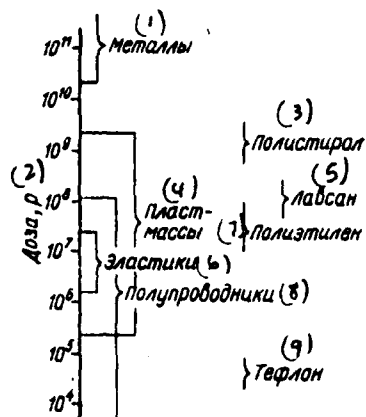


Fig. 1.5. Regions of the exposure doses of  $\gamma$ -radiation.

Key: (1). Metals. (2). Dose, p. (3). Polystyrene. (4). Plastics. (5). Lavsan [99sp06 - polyethylene terephthalate film, Soviet equivalent of Dacron]. (6). Elastics. (7). Polyethylene. (8). Semiconductors. (9). Teflon.

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### 1.3. Change in the electrophysical characteristics of materials during irradiation.

The electrophysical characteristics of materials change under the influence of irradiation as a result of the ionization of atoms and molecules of substance, damage of their structure, and also as a result of the course of secondary physicochemical processes in the materials. In this case can occur both temporary/time (reversible) and constant (not reversed, or residual/remanent) changes.

The reversible changes, as a rule, are the consequence of the ionization of the materials and the environment. They are developed in an increase in the concentration of charge carriers, which leads to the increase of stray current and an increase in the conductivity of materials. Irreversible injuries occur as a result of a change in structure of substance. The degree of the damage of solid bodies is determined by their structure and nature of chemical bond.

On metallic (conductor) materials the ionization virtually does

not have an effect. Noticeable residual/remanent changes in the parameters both electrical, and mechanical, are observed only with the large neutron fluxes - more than  $10^{20}$  neutrons/cm<sup>2</sup> [13]. The electrophysical characteristics of dielectrics are most subjected to change.

Dielectric materials, utilized in the construction/design of radio parts (materials of the foundations of resistors, condenser/capacitor dielectrics, of protective coatings, etc.), and their also surrounding air under the effect of the processes of ionization change their insulating properties. An increase in dielectric conductance is one of the most dangerous results of the effect of the ionizing radiations/emissions. An increase in the electrical conductivity causes an increase of the stray current in the process of irradiation. Simultaneously a change in the dielectric power factor occurs with an increase of the conductivity in some materials.

Dependence of stray current on the voltage/stress. The strength of current of leak/leakage in the process of irradiation depends on the applied voltage/stress. The experimental investigations of induced conductivity in the dielectrics both with the low (0.01-100 r/s) and at the high (more than  $10^4$  r/s) radiation dose rate showed the linear dependence of the induced current from the applied

voltage/stress with the strength of field to  $10^4$ - $10^5$  V/cm. During the irradiation the volt-ampere characteristic of insulation does not always pass through the origin of coordinates. For an example Fig. 1.6 gives the volt-ampere characteristics of some insulation during X-ray irradiation [17].

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The appearance of the induced current in the irradiated material in the absence of electric field (applied voltage/stress) is determined by a number of factors, which virtually from the quantitative side cannot be considered almost: form, sizes/dimensions and order of the location of elements/cells and materials in radio parts, arrangement/position of electrodes relative to the direction of radiant flux, and also form and energy spectrum of the ionizing radiation/emission.

Radiation conductivity of insulation. During the theoretical analysis of the radiationally induced conductivity in amorphous and crystal materials [14-17] the mechanism of the formation of conductivity, analogous to the process of photoconductivity in the crystals, usually is examined. In this analysis the principles of the zone structure of crystalline substance are utilized in essence.

Is opinion [18] that this approach is feasible not always for the organic materials. It is necessary to consider the value of the mobility of free charge carriers. With the mobility of larger than  $1 \text{ cm}^2/(\text{V}\cdot\text{s})$ , it is possible to apply band theory, for the smaller mobility must be used other models.

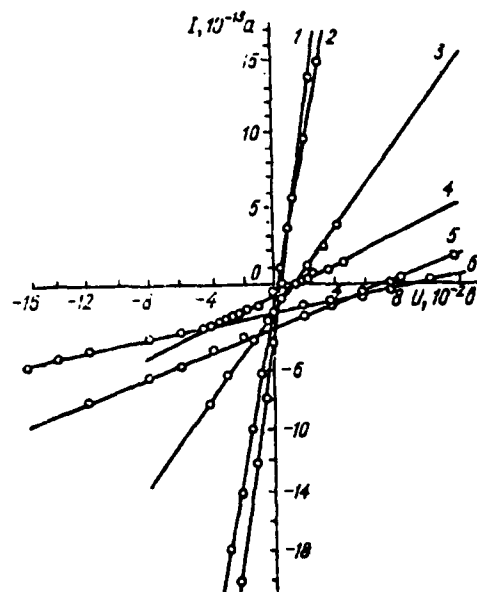


Fig. 1.6. The volt-ampere characteristics of solid dielectrics during the X-ray irradiation:  $n=120$  imp./min.;  $T=30^{\circ}\text{C}$ ; the thickness of samples/specimens  $d$ ; 1 - sulfur,  $d=0.025$  cm; 2 - teflon,  $d=0.1$  cm; 3 - polyethylene,  $d=0.3$  cm; 4 - mica,  $d=0.015$  cm; 5 - organic glass,  $d=0.45$  cm; 6 - polystyrene,  $d=0.5$  cm.

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The existing theories of induced conductivity do not make it possible to quantitatively describe processes in the dielectrics during the irradiation. Therefore for the practical calculations it is necessary to utilize experimental dependences with the appropriate empirical

coefficients.

If the character of a change in the radiation dose rate takes the form of square pulse (any duration), then induced conductivity first increases, then it reaches constant value, and it drops after the cessation/discontinuation of irradiation, approaching original value  $\sigma_0$ . A change in the conductivity of insulation under the effect of radiation/emission for the general case is shown in Fig. 1.7.

The build-up/growth of conductivity (section 1) occurs according to the law

$$\sigma - \sigma_0 = \sigma_p = \sigma_{p,y} (1 - e^{-t/\tau^*}), \quad (1.9)$$

where  $\sigma$  - conductivity of material;  $\sigma_p$  - induced conductivity at the moment of the effect of radiation/emission;  $\sigma_{p,y}$  - conservative value of induced conductivity;  $t$  - time;  $\tau^*$  - time constant of build-up/growth, which depends on the radiation dose rate and is equal to

$$\tau^* = K_0 P^{-a}$$

( $K_0$  and  $a$  - experimental constants).

The values of coefficient of  $K_0$ , depending on the power of exposure radiation dosage  $P$  for some materials are given in Table 1.3 [18].

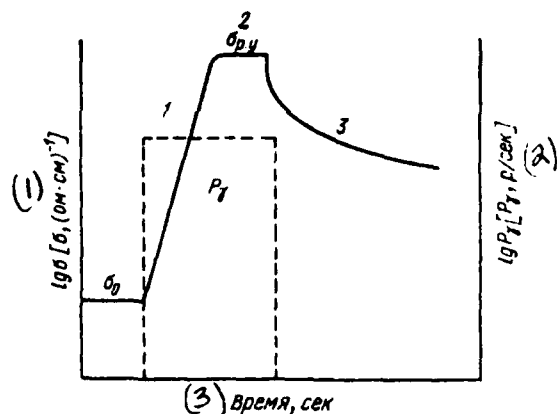


Fig. 1.7. Standard curve of a change in the conductivity of insulation under the effect of the ionizing radiation/emission. The character of the effect of the radiation dose rate is shown by dotted line.

Key: (1).  $(\Omega \cdot \text{cm})$ . (2).  $\text{r/s}$ . (3). Time, s.

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Coefficient  $a$  for these materials is equal to 0.5.

In the section of saturation 2 dependence takes the form

$$\sigma_{p, y} \rightarrow AP^\Delta, \quad (1.10)$$

where  $A$  and  $\Delta$  - empirical constants (table 1.4).

Decay in the induced conductivity usually has complicated dependence on the time and can be represented by the set/dialing of certain quantity of exponential curves [18]:

$$\sigma_p = \sigma_{p,y} \sum_{i=1}^n K_i e^{-t/\tau_i}, \quad (1.11)$$

where  $n$  - number of discrete/digital time constants;  $K_i$  - weight factor, which determines the contribution of the  $i$  time constant in the process of reduction of conductivity;  $\tau_i$  -  $i$  time constant of decay. It is considered in a number of cases that the decay is better described by the hyperbolic law of form [19]

$$\sigma_p = \frac{\sigma_{p,y}}{1 + bt^n}. \quad (1.12)$$

The time, during which the induced current drops in 10 and 100 times at a radiation dose rate 7 r/min (X-radiation) and a temperature of 80°C, for some materials is given in table 1.5 [19-22].

Table 1.3.

(1) Материал	(2) Диапазон мощности экспозиционной дозы, рад/сек ( $H_2O$ )	$K_0$
Эпоксидная смола (3)	$1,7 \pm 3 \cdot 10^3$	135
Полистирол (4)	$0,3 \pm 3 \cdot 10^3$	60
Полиэтилен (5)	$0,02 \pm 3 \cdot 10^3$	45

Key: (1). Material. (2). Power range of exposure dose, rad/s ( $H_2O$ ).

(3). Epoxy resin. (4). Polystyrene. (5). Polyethylene.

Table 1.4. Values of coefficients of A and  $\Delta$  for different insulation.

(1) Материал	(2) Диапазон мощности экспозиционной дозы, р/сек	(3) Темпера- тура ма- териала, °C	(4) $A, \frac{(\Omega \cdot \text{cm})^{-1}}{(p/\text{сек})\Delta}$	$\Delta$
Полиамид (5)	$1,8 \cdot 10^{-3} - 6 \cdot 10^3$	40	$5,8 \cdot 10^{-18}$	1,1
Полипропилен (6)	$1,8 \cdot 10^{-3} - 6 \cdot 10^3$	40	$3,8 \cdot 10^{-17}$	0,88
Полистирол (7)	$1,7 \cdot 10^{-3} - 5 \cdot 10^3$	40-60	$4 \cdot 10^{-17}$	0,97
Полиэтилен (8)	$8,3 \cdot 10^{-3} - 1,7 \cdot 10^3$	40-60	$(5,2-16) \cdot 10^{-18}$	0,74
Фторопласт (9)	$1,8 \cdot 10^{-3} - 6 \cdot 10^3$	40	$1,2 \cdot 10^{-18}$	1,0
Эпоксидная смола (3)	$1,7 - 4,2 \cdot 10^3$	40-60	$3,3 \cdot 10^{-17}$	1,0

Key: (1). Material. (2). Power range of exposure dose, r/s. (3).

Temperature of material, °C. (4).  $A (\Omega \cdot \text{cm})^{-1} / (r/s)\Delta$ . (5). Polyamide.

(6). Polypropylene. (7). Polystyrene. (8). Polyethylene. (9). Teflon.

(10). Epoxy resin.

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The duration of decay after the cessation/discontinuation of irradiation to the specific level depends on the radiation dose rate,

temperature and material. For example, in the inorganic materials the induced current drops considerably more rapid than in the organic ones (see Table 1.5).

In general form the dependence of induced conductivity on time and radiation dose rate (at constant temperature) includes all three processes: build-up/growth, conservative value and decay examined. If we represent radiation effect in the form of the single step function  $U(t)$ , then it is possible to record the general/common/total expression for the induced conductivity in the following form:

$$\begin{aligned} \sigma(t, P) = & U(t) \sigma_0 + U(t - t_0) [\sigma_2(t - t_0, P) - \sigma_1(t)] + \\ & + U(t - t_1) [\sigma_3(t - t_1) - \sigma_2(t - t_0, P)], \end{aligned} \quad (1.13)$$

where  $\sigma_0$  - initial dark conductivity in the material;  $\sigma_2(t - t_0, P)$  - the function, which corresponds to build-up/growth and conservative value of conductivity;  $\sigma_3(t - t_1)$  - function, which describes the restoration/reduction of conductivity (decay);  $T$  - absolute temperature;  $t_0$  - time, which corresponds to the beginning of irradiation;  $t_1$  - time of the cessation/discontinuation of instruction.

The dependence of induced conductivity on the temperature is described by the same formula as for the fundamental conductivity, namely

$$\sigma_p = N(P)e^{-W/kT} \quad \text{and} \quad \sigma_0 = N_0e^{-W_0/kT}, \quad (1.14)$$

where  $N(P)$  - the power function of radiation dosage, proportional to the concentration of charge carriers;  $N_0$  - function, proportional to the concentration of charge carriers (without the irradiation);  $W_0$  and  $W$  - energy of the activation of conductivity to and during the irradiation respectively.

The energy of activation  $W$  of induced conductivity during irradiation several times of less than the energy of the activation of the fundamental conductivity  $W_0$ . The corresponding values of the activation energies for some materials are given in Table 1.6 [19-22].

Table 1.5. Decay time in the induced conductivity for different insulation, h.

(1) Материал	(2) Уменьшение проводимости	
	(3) в 10 раз	(4) в 100 раз
(4) Полистирол	3	20
(5) Фторопласт-4	6	35
(6) Лавсан	3	33
(7) Слюда	(8) Несколько секунд	--

Key: (1). Material. (2). Decrease of conductivity. (3). once. (4). Polystyrene. (5). Teflon. (6). Lavsan. (7). Mica. (8). Several seconds.

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With a change in the radiation dose rate the energy of activation  $W$ , as is evident from Fig. 1.8 (based on the example of polystyrene), virtually it does not change.

Actually/really, the inclinations/slopes of dependences  $\lg \sigma_p = f(1/T)$ , which are determined by  $W$ , they remain constants; are variable only the values of function  $N(P)$  with a change in the radiation dose rate in connection with a change in the concentration of free charge carriers.

Table 1.6. Energy of the activation of induced conductivity before the irradiation and during irradiation by dose with the power of 0.1 r/s, eV.

(1) Материал	(2) До облучения	(3) При облучении
	$W_0$	$W$
(4) Полистирол	1.2	0.44
(5) Фторопласт-4	1.1	0.5
(6) Лавсан	1.3	0.2
(7) Слюда	0.45	0.18

Key: (1). Material. (2). Before irradiation. (3). During irradiation. (4). Polystyrene. (5). Teflon. (6). Lavsan. (7). Mica.

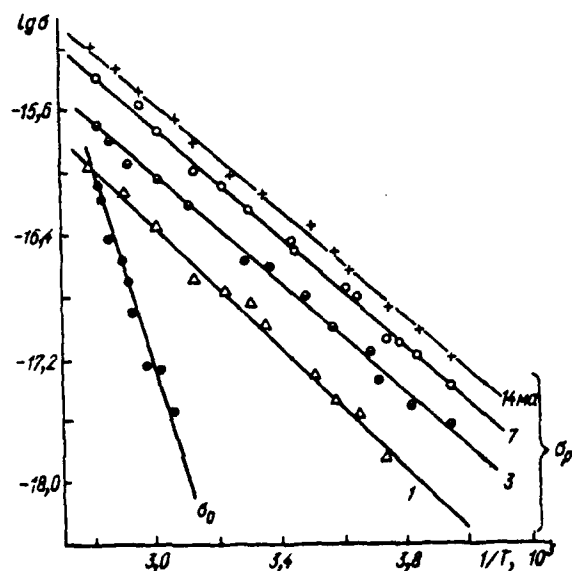


Fig. 1.8. Temperature dependence of initial  $\sigma$ , and induced electrical conductivities in polystyrene. Numerals in straight lines indicate the strength of current of X-ray tube.

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Essential difference in the activation energies leads to the fact that the relative change in the insulation resistance is the greater, the lower the temperature, at which is conducted the irradiation, although an absolute change in the insulation resistance grows/rises both with the increase in the radiation dose rate and with an increase in the temperature of the irradiated article.

Fundamental component of induced conductivity. The induced conductivity has two components: "instantaneous", which is determined by the straight/direct change-over of carriers into the conducting state under the effect of radiation/emission, and "delayed", connected with the thermal excitation of the carriers, seized by traps.

The lifetime of free carriers in insulation by order of value is equal to  $10^{-10}$ - $10^{-12}$  s [50]. Respectively instantaneous component must increase and drop virtually simultaneously with build-up/growth and decay in the emission impulse, and the deferred-action processes of build-up/growth and decay are explained by the effect of delayed component.

It follows also from nature of these phenomena that the value of

instantaneous component must not in the first approximation, depend on the duration of irradiation. These dependences are important for delayed component.

Thus, a change in the duration of irradiation, especially upon transfe. from the so-called continuous to the pulse irradiation, and also a change in the temperature they must lead not only to a change in conservative value of induced conductivity, but also values, which concern the time of establishment and decay as a result of changing the relative contribution to the total current of instantaneous and delayed component. It is obvious that the effect of delayed component decreases with the decrease of temperature and duration of irradiation.

From the dependences, given in Fig. 1.9, according to the results of the studies of the samples/specimens of polystyrene and polystyrene capacitors on the radiation sources with different duration of the effect of radiation/emission, but one and the same power of exposure radiation dosage it is evident that with the decrease of the duration of the pulse of irradiation decreases the value of induced conductivity.

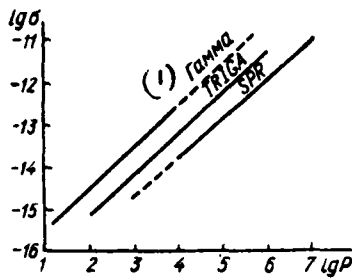


Fig. 1.9. The dependence of induced conductivity on the radiation dose rate on different sources of the irradiation: gamma - cobalt-60; TRIGA - pulse nuclear reactor with a duration of the pulse of 10 ms (on half of the pulse amplitude); SPR - pulsed nuclear reactor with a duration of the pulse of 45  $\mu$ s.

Key: (1). Gamma.

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Thus, the conductivity of material during irradiation by impulse/momentum/pulse 45  $\mu$ s (reactor SPR) approximately/exemplarily to one order less than the conductivity during irradiation by impulse/momentum/pulse 10 ms (reactor TRIGA) and on two orders is less in comparison with the irradiation on the steady source of  $\gamma$ -radiation Co<sup>60</sup>.

On the basis of the results of experimental investigations, the

authors of work [23] consider that the mean life of the seized current carriers is more than 12 ms. However, about other experimental investigations, which confirm these data, to us it is unknown. However, the analysis of the available results of measurements on different radiation sources does not give so considerable and regular a dependence on the duration of irradiation.

On two components of conductivity it is possible to represent conservative value of induced conductivity in the form [18]

$$\sigma_p^* = \sigma_m + \sum_i \sigma_{di}, \quad (1.15)$$

where  $\sigma_p^* = \sigma_p / \epsilon \epsilon_0$ , s;  $\sigma_m$  — instantaneous component of induced conductivity;  $\sigma_{di}$  — delayed component of induced conductivity.

Dependence of the instantaneous component of conductivity on the radiation dose rate takes the form

$$\sigma_m = K_m P^\Delta, \quad (1.16)$$

where  $K_m$  and  $\Delta$  — experimental coefficients.

Assuming that decay in the induced current occurs exponentially and has only one time constant  $\tau_{en}(i=1)$ , equation for delayed component can be represented in the form

$$\frac{d\sigma_i}{dt} = K_i P^\Delta - \frac{\sigma_i}{\tau_{en}}. \quad (1.17)$$

For the square pulse with a duration of  $t_n$  when  $t_n \ll \tau_{en}$ , value

is equal to

$$\sigma_3 = K_3 I_0 e^{-t/\tau_{cn}} = \sigma_{30} e^{-t/\tau_{cn}}. \quad (1.18)$$

In the general case

$$\sigma_3 = K_3 \int_{t'=0}^t P^{\lambda}(t') e^{-(t-t')/\tau_{cn}} dt'. \quad (1.19)$$

The experimental results of the measurements of the corresponding constants for different materials are given in Tables 1.7 and 1.8 [18]. measurements were conducted in the samples/specimens of the capacitors, whose capacity/capacitance was in the limits from 0.002 to 3.3  $\mu\text{F}$ . Duration of the pulse of X-radiation 0.2  $\mu\text{s}$ . Linear electron accelerator (LEU) had a duration of pulse 4.5  $\mu\text{s}$  and an energy of electrons 25 MeV.

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The form of the emission impulse of reactor TRIGA was funnel-shaped with the duration on the half-height of impulse/momentum/pulse 10 ms (during the computations the form of emission impulse it was accepted as rectangular).

The short-lived component of delayed component (parameters, which characterize it, they are given in table 1.8 with index 1) was observed during irradiation by X-radiation, also, on the linear accelerator, and long-lived (index 2) - during irradiation on the pulse reactor.

Table 1.7. Experimental data on the instantaneous component of induced conductivity on different sources of the ionizing radiations/emissions.

(1) Диэлектрик	$10^{-2} \frac{\text{сек}^{-1}}{(2)}$	$\Delta$	$10^{-2} \frac{K_M^1}{(\rho \Delta \cdot (K_M^1) - \Delta)^{-1}}$	$\frac{K_M^2}{K_M^1}$	$\frac{K_M^3}{K_M^1}$
(3) Окись тантала	50 (10-100)	1,0	8 (4-12)	0,08	0,04
(4) Керамика (BaTiO <sub>3</sub> )	20 (15-30)	0,89	60 (30-80)	0,02	0,06
(5) Слюда	3 (2,7-3,3)	0,85	14 (10-17)	0,09	0,11
(6) Лавсан	5,4 (0,4-1,6)	0,86	2 (1-4)	2,0	3,0

Note. Without the brackets - probable values of values, and in the brackets - possible limiting values, obtained according to the experimental data.

Key: (1). Dielectric. (2). s. (3). Oxide of tantalum. (4). Ceramics (BaTiO<sub>3</sub>). (5). Mica. (6). Lavsan.

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FOOTNOTE 1. X-radiation; given for the rate doses  $5 \cdot 10^5$  r/s, measured in the center of capacitor.

2. LEU; electrons with energy 25 MeV at dose rate from  $1 \cdot 10^7$  to  $2 \cdot 10^7$  r/s.

<sup>1</sup>. Pulse reactor TRIGA; dose  $5 \cdot 10^5$  r; maximum rate of dose  $4 \cdot 10^7$  r/s. ENDFOOTNOTE.

Table 1.8. Experimental data on the delayed component of induced conductivity on different sources of the ionizing radiations/emissions.

(1) Диэлектрик	$K_{31} \cdot 10^{-4}$ ( $\rho \Delta \cdot (K_{31}^2 - \Delta) - 1$ )	$K_{31} K_{31} \cdot 10^{-4}$ $10^{-1}$	$\tau_1 \cdot 10^{-4}$ сек (2)	$K_{32} \cdot 10^{-4}$ ( $\rho \Delta \cdot (K_{32}^2 - \Delta) - 1$ )	$\tau_2 \cdot 10^{-4}$ сек (3)
(3) Окись тантала	1,2 (0,4—24)	0,5	4 (3—5)	0,8 (0,6—0,9)	1,2 (0,6—1,4)
(4) Керамика BaTiO <sub>3</sub>	3 (0,1—9)	0,7	3 (0,8—3,5)	20 (2,5—60)	1,1 (0,9—1,3)
(5) Слюда	0,4 (0,3—5)	0	15	3,0	1,3
(6) Лавсан	1,2 (0,9—1,3)	20	4 (3,3—5)	11 (4—16)	1,0

Note. Without the brackets - probable values of values, and in the brackets - possible limiting values, obtained according to the experimental data.

Key: (1). Dielectric. (2). s. (3). Oxide of tantalum. (4). Ceramics BaTiO<sub>3</sub>. (5). Mica. (6). Lavsan.

FOOTNOTE <sup>1</sup>. X-radiation; given for the rate doses  $5 \cdot 10^5$  r/s, measured in the center of capacitor.

3. LEU; electrons with energy 25 MeV at dose rate from  $1 \cdot 10^7$  to  $2 \cdot 10^7$  r/s.

4. Pulse reactor TRIGA; dose  $5 \cdot 10^5$  r; maximum rate of dose  $4 \cdot 10^7$  r/s. ENDFOOTNOTE.

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The constant value of the time of the short-lived component of conductivity  $\tau_1$  in mica was insignificant in experiments on the linear accelerators. During irradiation of ceramic material  $\tau_1 \approx 24 \mu s$  (radiation dose rate it was  $1 \cdot 10^7$  r/s). At higher radiation dose rates in mica and ceramics the time constant became considerably less.

For other tested materials on LEU at the radiation dose rate  $1 \cdot 10^7$  r/s  $\tau_1$  was two times more than for the X-radiation, but at the rate of dose  $2 \cdot 10^7$  r/s it decreased to the value, compared or even lower than during the X-radiation.

Table 1.9. Generalized data on the instantaneous component of induced conductivity.

(1) Диэлектрик	$K_m \cdot 10^{-4}$ $\rho \Delta \text{ см}^{-1} \cdot \Delta$ (2)	$\Delta$	$\epsilon$	(3) Излучение	(4) Диапазон мощности дозы, р/сек
(5) Оксид тантала	0,6 (0,1—1,1)	1	25	(6) Реакторное <sup>1</sup>	$3 \cdot 10^4 - 7 \cdot 10^7$
(7) Оксид алюминия	0,5 (0,3—1,0)	1	7	"	$5 \cdot 10^5 - 3 \cdot 10^7$
(8) Слюда	0,5 (0,1—5,0)	1	8,4	"	$6 \cdot 10^5 - 6 \cdot 10^7$
(9) Керамика BaTiO <sub>3</sub>	7 (1,4—14)	0,89	20	"	$1 \cdot 10^7 - 5 \cdot 10^7$
Слюда (10)	20 (10—40)	0,83	6,8	"	$3 \cdot 10^5 - 4 \cdot 10^7$
(12) Лавсан	8 (6,5—9,5)			(11) Рентгеновское	$10^{-2} - 10^4$
	5 (0,6—35)	0,86	3,0	(6) Реакторное	$6 \cdot 10^4 - 4 \cdot 10^7$
(13) Фторопласт-4	0,8 (0,1—5,6)			(11) Рентгеновское	$10^{-2} - 10^4$
	90 (23—180)	0,85	2,0	(6) Реакторное	$10^{-2} - 2 \cdot 10^4$
	400 (130—800)			(11) Рентгеновское	$10^{-2} - 1$
(14) Полистирол	20 (2,3—28)	0,96	2,4	(6) Реакторное	$2 \cdot 10^{-2} - 5 \cdot 10^4$
(15) Витамины Q <sub>2</sub>	7 (2—24)	0,94	11	(11) Рентгеновское	$10^{-2} - 1$
	6			(6) Реакторное	$10^1 - 7 \cdot 10^7$

Note. Without the brackets - probable values of values, and in the brackets - limiting values, obtained according to the experimental data.

Key: (1). Dielectric. (2). s. (3). Radiation/emission. (4). Power range of dose, r/s. (5). Oxide of tantalum. (6). Reactor<sup>1</sup>.

FOOTNOTE <sup>1</sup>. Reactor radiation/emission -  $\gamma$ - and neutron radiation/emission of nuclear reactors. ENDFOOTNOTE.

(7). Oxide of aluminum. (8). Glass. (9). Ceramics BaTiO<sub>3</sub>. (10). Mica. (11). X-ray. (12). Lavsan. (13). Teflon. (14). Polystyrene. (15). Vitamin Q<sup>1</sup>.

FOOTNOTE <sup>1</sup>. Low-molecular polyisobutylene, utilized for the saturation of paper capacitors. ENDFOOTNOTE.

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On the basis of the analysis of the available results, given table 1.7, and other data obtained in the series/row of sources, mainly pulse radiation/emission, in table 1.9 gives the generalized data on instantaneous component of induced conductivity [18]. The available results on the measurement of decay in the current after short emission impulse are scarce. It is difficult to systematize these separate experimental data. It is possible to only assume that at the radiation dose rates 10<sup>4</sup>-10<sup>7</sup> r/s and duration of pulse 0.1-5  $\mu$ s the time constant of decay for the majority of organic materials is equal to 0.1-1 ms. In inorganic materials it several times (to one order) less. The decay time decreases with an increase in the dose rate. A change in the time constant of decay occurs, probably, according to the law

$$\tau_{en} = b/P^n,$$

(1.20)

where  $b$  and  $\delta$  - experimental constants, moreover  $\delta$  is less than one and, possibly, it is nearer to 0.5.

On the basis of the experimental results, is possible to count that during the pulse irradiation basic part of induced conductivity during the impulse/momentum/pulse is instantaneous component of conductivity, and delayed component determines decay, i.e., a gradual decrease in the conductivity in the time after radiation effect on insulation.

Radiation conductivity of air. In air under the effect of the ionizing radiation/emission also appear free charge carriers - pairs - positive ion and electron.

If in air is a system of electrodes, to which the potential is applied, then in the region of the average/mean strengths of field the part of the charge carriers, formed due to the ionization, will depart to the electrodes, and recombine part in the interelectrode gap/interval. Boag obtained analytical dependence for calculating the strength of ionizing current in air between the plane-parallel electrodes taking into account current leak to the electrodes and with the use of experimental values of the coefficient of ion recombination and mobilities of positive and negative ions  $\mu_+$  and  $\mu_-$ .

[25]

$$I = \frac{0.66 P_{\gamma} d S \cdot 10^9}{\sqrt{1 + 2.5 \cdot 10^3 \frac{P_{\gamma} d^4}{U^3}}} \quad (1.21)$$

where  $I$  - current of leak/leakage, a;  $P_{\gamma}$  - power of the exposure dose of  $\gamma$ -radiation, r/s;  $d$  - distance between electrodes, cm;  $S$  - area of flat electrode, cm<sup>2</sup>;  $U$  - applied voltage/stress, V.

The given methods of determining the conductivity of electrical insulating materials (reversible changes) in the process of action of the ionizing radiations/emissions allow with the acceptable precision/accuracy for the fundamental dielectrics to perform the necessary calculations.

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Unfortunately, a change in the electrophysical properties of materials as a result of the course in them of the irreversible processes can be evaluated in the majority of the cases only qualitatively.

#### 1.4. Effect of physicochemical processes on the operating characteristics of materials.

A change in the physical and chemical properties occurs under

the radiation effect in the materials, which leads to the disturbance/breakdown of the operating parameters.

The radiation heating of materials as usual heating, leads to a change in their ohmic resistance. Value and direction of this change depend on the temperature coefficient of material and in the limits of the permissible temperatures of the operation of radio parts are proportional to an increase in the temperature and, consequently, also the powers of the exposure dose of  $\gamma$ -radiation.

At a prolonged effect of penetrating radiation and an elevated temperature is reduced service life, descends reliability, the mechanical stability of materials under the conditions of vibration, impacts, centrifugal loads. The most considerable overheatings are characteristic for the massive articles. Therefore the use/application of different kind of the heat-transferring elements/cells (especially from the heavy materials) contributes to supplemental heat and, consequently, also to a change in the operating parameters. Furthermore, heating materials, including radiation, contributes to the restoration/reduction of disturbances/breakdowns in crystal lattice, since the process of thermal annealing occurs. Velocity and space of reduction processes depend on material, form of damage, degree of damage and temperature of heating article.

The chemical changes in the materials, which occur as a result of oxidation processes, destructions, structurings, formations of new chemical compounds, also act on operating characteristics of materials. The oxidation of the surfaces of materials considerably raises the resistor/resistance of contact pairs. Upon the galvanic decomposition, which occurs as a result of electrochemical corrosion in the place of the contact of two metals, the appearance of a current of corrosion is possible. Some materials can be damaged by acids, which appear usually during interaction of the gases separated from the materials with the moisture of the environment.

The possible forms of physicommechanical changes, characteristic for the materials, subjected to the processes of destruction and structuring, are given in Table 1.10.

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Changes in the physicommechanical characteristics of materials lead to a change in the operating characteristics of radio parts or cause separate disturbances/breakdowns in them. Thus, the decrease of the mechanical strength of materials can affect the service life of radio parts under the conditions of mechanical loads (vibration, impacts, linear accelerations). For example, teflon after irradiation and application of mechanical load will be dispersed.

Table 1.10. Physicomechanical changes in the organic materials under the effect of the ionizing radiations/emissions.

(1) При процессах структурирования	(2) При процессах деструкции
(3) Увеличение модуля упругости	(4) Уменьшение модуля упругости
(5) Возрастание коэффициента вязкости	(6) Снижение коэффициента вязкости
(7) Повышение предела прочности при растяжении	(8) Уменьшение предела прочности при растяжении
(9) Понижение относительного удлинения при разрыве	(10) Повышение относительного удлинения при разрыве
(11) Повышение твердости	(12) Понижение твердости
(13) Понижение растворимости	(14) Повышение растворимости
(15) Повышение температуры размягчения	(16) Уменьшение сопротивления на срез
(17) Увеличение хрупкости	(20) Иногда возможно
(18) Увеличение плотности	(19) Увеличение хрупкости
(19) Газообразование	(20) Газообразование
(21) Иногда возможно	(21) Пылеобразование
(22) Пылеобразование	(22) Образование микротрещин
(23) Образование микротрещин	(23) Расслаивание
(24) Расслаивание	

Key: (1). During the processes of structuring. (2). During processes of destruction. (3). Increase in modulus of elasticity. (4). Decrease of modulus of elasticity. (5). Increase of coefficient of viscosity/ductility/toughness. (6). Decrease in coefficient of viscosity/ductility/toughness. (7). Increase in ultimate tensile strength. (8). Decrease of ultimate tensile strength. (9). Decrease in elongation at rupture. (10). Increase in elongation at rupture. (11). Increase in hardness. (12). Softening. (13). Decrease in solubility. (14). Increase in solubility. (15). Increase in softening temperature. (16). Decrease of resistor/resistance to shear/section. (17). Increase in brittleness. (18). Increase in density. (19). Gas formation. (20-21). It is sometimes possibly. (22). Dust formation. (23). Formation/education of microcracks. (24). Stratification.

Table 1.11. Properties of ionic structures, which depend on the radiation effects.

(1) Структурные и механические	(2) Электронные и дырочные	(3) Свойства, характеризующие скорость процесса
(4) Кристаллическая структура	(5) Парамагнетизм	(6) Диффузия
(7) Параметр решетки	(8) Оптическое поглощение	(9) Ионная электропроводность
(10) Плотность	(11) Фотопроводимость	(12) Фазовые превращения
(13) Твердость	(14) Электропроводность	(15) Химические реакции
(16) Пластичность и прочность	(17) Диэлектрическая проницаемость	—
(18) Фононовая теплопроводность	(19) Электрическая прочность	—
(20) Внутреннее трение	(21) Угол диэлектрических потерь	—
—	(22) Люминесценция	—

Key: (1). Structural and mechanical. (2). Electronic and hole. (3). Properties, which characterize rate of processes. (4). Crystal structure. (5). Paramagnetism. (6). Diffusion. (7). Lattice parameter. (8). Optical absorption. (9). Ionic conductivity. (10). Density. (11). Photoconductivity. (12). Phase transformations. (13). Hardness. (14). Electrical conductivity. (15). Chemical reactions. (16). Plasticity and strength. (17). Dielectric constant. (18). Phonon thermal conductivity. (19). Dielectric strength. (20). Internal friction. (21). Dielectric loss angle. (22). Luminescence.

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Gas evolution in the closed volume of capacitors can lead to their mechanical damages. The entry/incidence of dust-figurative

products to the contacts causes the disturbance/breakdown of contact in the variable/alternating resistors. The formation/education of microcracks, stratification and multiplexing of materials disrupts airtightness it contributes to the penetration of the moisture and other aggressive or oxidizing media to the active parts of the radio parts. For the materials with the ionic structure, which include ceramic materials, the possible external manifestations of radiation effects are given in Table 1.11 [27].

The results of the effect of the ionizing radiations/emissions on the materials, entering the construction/design of radio parts, are such in general terms. A change in the characteristics of resistors and capacitors is frequently determined by the interconnection of different elements of construction/design and by a respectively complex change in the properties of materials, utilized in this article.

Results theoretically and the experimental investigations of the effect of the penetrating radiations/emissions on the resistors and the capacitors are examined in the following chapters.

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## Chapter 2.

Action of penetrating radiation on the resistors.

### 2.1. Short characteristic of resistors.

Gamma- and neutron radiations/emissions cause the reversible or irreversible (in full or in part) changes in the ohmic resistance of resistors. These changes can be caused by the following processes: by a change in the electrophysical characteristics of the material of conducting element, and also insulation, used in the construction/design of resistor; by a considerable increase of the electrical conductivity of the materials of the construction/design of resistor as a result of ionization; by a sharp increase in the electrical conductivity of air or another medium of that surrounding resistor, as a result of ionization.

Character and degree of a change in the ohmic resistance of resistors under the effect of  $\gamma$ - and neutron radiations/emissions

depend on the radiation characteristics, structural/design and technological special features/peculiarities of resistors and materials used in them.

The produced resistors can be at present subdivided into three basic groups, which are characterized by the technological principles of obtaining, by initial materials and, correspondingly, by technical special features/peculiarities.

The first group includes lamellar resistors on the base of the thin conducting films, precipitable by some or another method to the insulating foundations. As the initial materials for these films the widest use received three groups of the materials, which possess a sufficient heat resistance, the chemical inertness and other technological special features/peculiarities, which make with possible ones their industrial use:

1) crystal carbon, called sometimes pyrolytic or bright, and borocarbon; 2) the noble or weakly-oxidizing metals and their alloys (gold, palladium, platinum, rhodium, chromium, nickel, titanium, tungsten, etc.), they recently won acceptance also nitrides of chromium of titanium, tantalum, carbides and silicides of metals; 3) oxides of metals, in particular the dioxide of tin.

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As the foundations for such resistors are utilized the well sintered porcelain with the low content of oxides of alkali metals, zirconium and aluminaceous ceramics, and also some types of glass. Carbonic, boron-carbon, metal-film, metal-oxide and other types of lamellar (thin-film) resistors are distinguished depending on the materials used for the conducting films.

The second group unites the composite resistors, obtained on the base of the compositions, which consist of the mechanical mixture of powder-like conductor with its connecting/cementing dielectric, organic or inorganic. Are most widely used compositions from different form of carbon black and graphites with the highly polymeric synthetic resins, predominantly thermosetting: silicon and phenol. Inorganic materials are utilized as the fillers. Most frequently are applied the following fillers; the dioxide of titanium, the dioxide of zirconium, powdered silica gel (silicon acid), sulfate barium, talc, mica flour, fine/small quartz sand, porcelain flour, powdered glass, etc. Depending on materials are distinguished the compositions: cermet, metal-glass, carbon-ceramic, varnished carbon black, etc. The thin-film and compound resistors compose the vast class of non-wire resistors. For the protection of these resistors from the moisture are applied the varnishes, enamels

and compounds, as a rule, organic origins (cresol-formaldehyde varnish, silicone varnish, glyptal-oil enamel).

Third group compose resistors with the conducting element from the wire and microwires on the base of alloys with the high specific resistor/resistance (Manganin, Nichrome, constantan, Fechrall) or precious metals. In recent years increasingly more frequent as the conducting element they are utilized microwire from different alloys and metals in fiberglass insulation, for which extensively are used the glass of the type "nonex" and "pyrex" on the base of oxides  $\text{SiO}_2$ ,  $\text{B}_2\text{O}_3$ ,  $\text{Na}_2\text{O}$ ,  $\text{Al}_2\text{O}_3$ . Foundations and frameworks/bodies of constant wire resistors in the majority of the cases are manufactured from the well sintered ceramics, polymeric materials and compounds (for example, plastic AG-4) are utilized for the filling and the protective housings. The outputs of resistors are manufactured from the stainless steel.

Variable/alternating resistors (potentiometers) compose special group. As the resistive element/cell of potentiometers are utilized the conducting plastics, varnish-carbon compositions, metal-oxide and metallic films, metal-glass tape/film and volumetric compositions, wire from the high-impedance alloys. Sliding contact is made usually of solid metal or of the conducting plastic (by larger part in the volumetric compositions). For foundations and frameworks/bodies of

potentiometers are utilized Getinax [Гетинакс - laminated paper-Bakelite insulating material], Textolite, the ceramics and different plastics.

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The most typical forms and the constructions/designs of the conducting elements of resistors are shown in Fig. 2.1. The volumetric version of construction/design is most widely used in the volumetric composite resistors, tape/film - in the thin-film low-resistance resistors (with the ratings not more than 1000  $\Omega$ ), spiral - in thin-film high-impedance resistors, horseshoe - in variable resistors (potentiometers).

Fundamental parameter of resistor - resistor/resistance, determined by construction/design and sizes/dimensions of conducting element and by properties of its materials. For the resistors of cylindrical form with the conducting element, plotted/applied to the surface, when the thickness of the conducting film is small in comparison with the diameter of foundation (Fig. 2.1b), the value of resistor/resistance is determined from the formula

$$R = \rho \frac{l}{\pi D b}, \quad (2.1)$$

where  $\rho$  - specific resistor/resistance of the conducting film;  $b$  -

thickness of the conducting film;  $l$  - length of the conducting film;  
 $D$  - diameter of foundation.

For changing the value of the resistor/resistance of thin-film resistors, in particular for an increase in the resistor/resistance, is utilized the method of the spiral cutting of conducting layer, and also the method of the cutting of the layer of next longitudinal furrows along the foundation (Fig. 2.1b and 2.1d). The method of spiral cutting is most widespread.

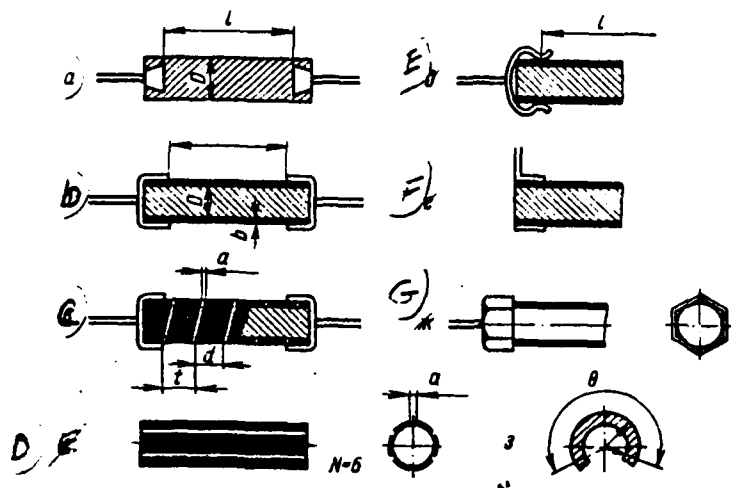


Fig. 2.1. Typical forms and construction/design of conducting elements of non-wire resistors: a) - massive (volumetric) element/cell; b, e, f, g - tape/film; c - tape/film spiral; d - tape/film with longitudinal gashes;  $\lambda$  - horseshoe.

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The resistor/resistance of resistor with the spiral cutting is designed from the formula

$$R = \rho \frac{N\pi D}{(t-a)b}, \quad (2.2)$$

where  $N$  - number of fillets of screw;  $t$  - spiral pitch;  $a$  - distance between the adjacent turns of conducting element.

For the resistor with the conducting element, carried out in the form of volumetric construction/design (Fig. 2.1a),

$$R = \rho \frac{4l}{\pi D^3}, \quad (2.3)$$

where D - diameter of conducting element.

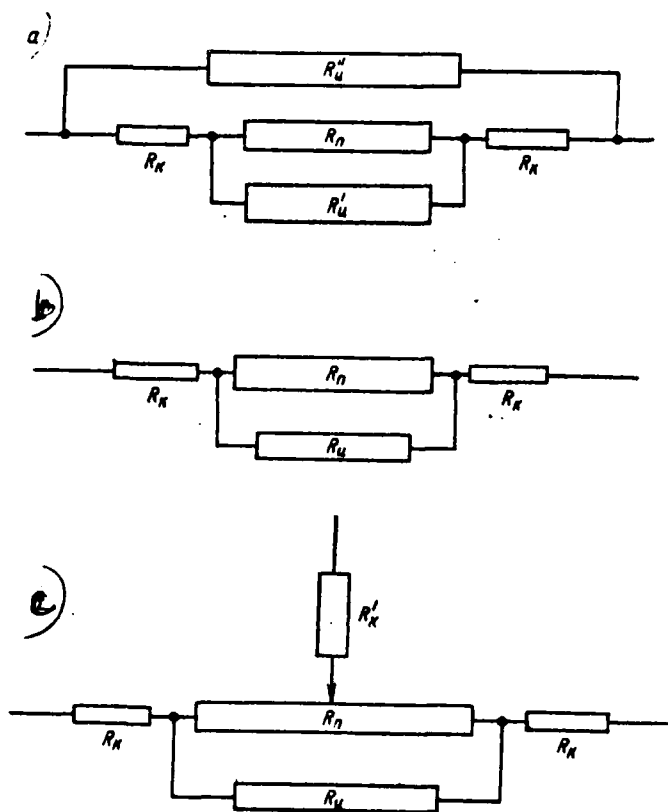


Fig. 2.2. Equivalent diagrams for direct current: a) - constant resistor; b) - fixed resistor, simplified; c) - variable/alternating resistor.

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For the horseshoe conducting element (Fig. 2.1h)

$$R = \frac{\rho}{b} \cdot \frac{r_2 + r_1}{r_2 - r_1} \cdot \frac{\pi \theta}{360}, \quad (2.4)$$

where  $r_1$  and  $r_2$  - inside and external radii of element/cell respectively;  $\theta$  - angle, hail, which corresponds to the conducting section of arc.

The resistor/resistance of wire resistors is defined by the length of wire  $l$ , by its specific resistor/resistance and by cross-sectional area:

$$R = \rho \frac{l}{S}. \quad (2.5)$$

In spite of comparative simplicity of the construction/design of resistor, in its general case should be considered as the system, into which the effective resistance strictly of resistive element/cell  $R_n$  enters as fundamental component/term/addend. Besides it, it is necessary to consider the following active components (Fig. 2.2) the resistor/resistance of make-before-break contact between resistive of elements/cells and metal insert/reinforcement  $R_k$ ; backs-out resistor of insulating foundation  $R'_n$  (in the volumetric construction/design it is absent) and protective coating  $R'_n$ , which for the simplification it is possible to replace with one resistor/resistance  $R_n$   $\left( R_n = \frac{R'_n R''_n}{R'_n + R''_n} \right)$ ; contact resistance between feeder brush and resistive element/cell in variable/alternating resistors  $R'_k$ .

## 2.2. Change of resisting the resistors as a result of the processes of ionization.

One of the manifestations of radiation effect - ionization of substance, as a result of which in the materials of the construction/design of resistor and in air surrounding resistor flow/occur/last the ionizing currents, which sharply increase the shunting effect of the conductivity of the materials of insulating foundation, the protective coatings also of air and calling the temporary/time decrease of the ohmic resistance of resistors. The effect of shunting becomes essential under the effect of high intensity radiation/emission. Thus, in the process of irradiation on the pulse reactor Godiva II with the duration on the half-height of the funnel-shaped impulse/momentum/pulse of  $\gamma$ -radiation of approximately 150  $\mu$ s and a power of exposure dose  $\sim 10^7$  of r/s the value of the ohmic resistance of high-impedance resistors (from 100 kilohm to 1 M $\Omega$ ) temporarily decreased, but changes carried the reversible character.

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Recovery time of the value of resistor/resistance to the original

value did not exceed 1-2 ms [29]. Fig. 2.3 shows the character of a change of resisting the high-impedance resistors in the process of pulse irradiation.

The analogous character of a change of the resistor/resistance in the process of pulse irradiation and its reduction after the cessation/discontinuation of the impulse/momentum/pulse of radiation was observed in the metal-film, metal-oxide, composite and wire resistors, prepared by different firms [10, 30, 31].

It is obvious that at the comparable power coefficients of the dose of  $\gamma$ -radiation the relative percentage of shunting becomes more essential, the higher the nominal resistor/resistance of resistor. Table 2.1 gives the dependence of a relative change of resisting the resistor on its nominal value during irradiation in reactor Godiva II (power of the exposure dose of the  $\gamma$ -radiation of approximately/exemplarily  $10^7$  r/s) [32].

A similar dependence of the value of a change of resisting the resistors from the rating was observed also in the process of the pulse irradiation of volumetric carbon resistors (for the duration of  $\gamma$ -impulse/momentum/pulse of approximately 200  $\mu$ s and in the exposure dose approximately/exemplarily  $1.8 \cdot 10^7$  r/s) [10]. The decrease of the resistor/resistance of high-resistance resistors (10 M $\Omega$ ) composed 86%

approximately/exemplarily, whereas for the resistors with a nominal resistor/resistance of 100 ohms it did not exceed 0.1%.

For the tape/film carbonic, metal-film, metal-oxide and composite resistors with the rating of 1 M $\Omega$  in the process of irradiation on reactor Godiva II at the power of the exposure dose of  $\gamma$ -radiation 10<sup>7</sup> r/s the maximum decrease of resistor/resistance reached 50%, while for the resistors with the rating of 100 kiloohm did not exceed 35% [33].

Table 2.1.

Dependence of a relative change in the value of the resistor/resistance of tape/film carbonic resistor from its nominal value.

Номинальное сопротивление резистора, ом (1)	$10^3$	$10^4$	$10^5$	$10^6$	$10^7$
Относительное изменение сопротивления резистора, % (2)	0	-5	-20	-48	-85

Key: (1). Nominal resistor/resistance of resistor, ohms. (2). Relative change of resisting resistor, %.

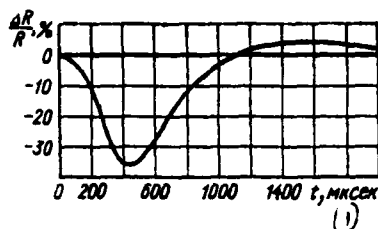


Fig. 2.3. Character of change of resisting resistor in process of pulse irradiation in reactor.

Key: (1).  $\mu s$ .

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During irradiation of the resistors of analogous types (at the power of the exposure dose of  $10^7$  r/s) the resistor/resistance of resistors with the rating of  $1 M\Omega$  decreased by 70%, while in ten-kilohm resistors the decrease of resistor/resistance did not exceed 2-5% [10].

The observed dependence of the value of a change of resisting the resistors from the rating under the effect of high intensity radiation/emission (for one and the same type of resistive element/cell) testifies about its direct coupling with the design parameters of resistor and the electrophysical characteristics of the

utilized materials.

Actually/really, the value of the resistors/resistances of shunts, which appear in resistors of one and the same type, rating and prepared on one technology, but with different dissipated powers (with different overall dimensions) during irradiation in the pulse reactor, considerably they are distinguished (Table 2.2).

At the same time the value of a change of resisting the resistors under the radiation effect to a considerable degree is determined by the rate of the dose of  $\gamma$ -radiation.

The character of this dependence for the metal-film resistors of different ratings under the influence of the impulse/momentum/pulse of  $\gamma$ -radiation is visible from Table 2.3.

It is noticed that the protection of the metallic conclusions/outputs of resistors and places of soldering in the diagrams by insulating varnishes or by another insulation and especially the pressing of resistors by epoxy resin decrease the effect of high intensity radiation/emission on the value of a change in their resistor/resistance.

Since, as shown by given data, most considerable reversible

changes in the resistor/resistance, caused by ionizing processes, they occur in the high-impedance resistors, whose overwhelming majority non-wire thin-film resistors, compose, let us examine the processes, which take place in these resistors during irradiation.

Table 2.2.

Dependence of the value of back-out resistor from the overall dimensions (from the nominal dissipated power).

(1) Номинальная мощность рассеяния резистора, Вт	(2) Величина сопротивления шунта, обусловленного ионизацией, $10^7$ Ом
0,25	5
0,5	2
1	1,1
2	0,8

Key: (1). Nominal dissipated power of resistor, W. (2). Value of resistor/resistance of shunt, caused by ionization,  $10^7$  ohms.

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High-impedance thin-film resistors, as a rule, have the resistive element of the spiral construction/design (see Fig. 2.1c).

Interturn gap is the most dangerous section of construction/design for these resistors from the point of view of the onset of the considerable ionizing stray currents.

Table 2.3.

Dependence of the value of a change of resisting the metal-film resistors of different ratings, but one dimension from the power of the exposure dose of  $\gamma$ -radiation.

(1) Мощность экспозиционной дозы $\gamma$ -излучения, $\text{p/sv}$	(2) Относительное изменение сопротивления резисторов с номинальным сопротивлением, %	
	220 $\Omega$ (3)	270 $\text{k}\Omega$ (4)
$5 \cdot 10^6$	-1	-8
$10^7$	-2	-13
$10^8$	-7	-36
$2 \cdot 10^8$	-8	-50

Key: (1). Power of the exposure dose of  $\gamma$ -radiation,  $\text{r/s}$ . (2). Relative change of resisting resistors with nominal resistor/resistance, %. (3).  $\Omega$ . (4).  $\text{k}\Omega$ .

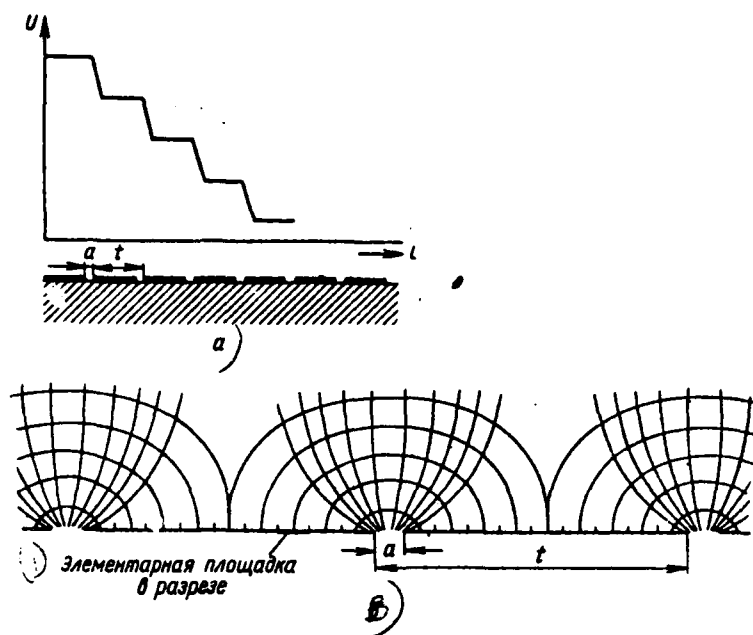


Fig. 2.4. Voltage distribution in spiral-shaped resistor (a) and electric field between adjacent turns of uninsulated conducting spiral of this resistor (b):  $a$  - interturn gap;  $t$  - space of cutting of spiral.

Key: (1). Surface element in the section/cut.

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The presence of spiral cutting causes the considerable distortion of electric field, during which in the interturn gaps/intervals, where

all applied voltage/stress is distributed, put the considerable stresses of field (Fig. 2.4a) [34, 35].

The voltage/stress between the adjacent turns of the spiral

$$U_a = \frac{U}{N} = \frac{Ut}{l}, \quad (2.6)$$

where  $U$  - voltage/stress, applied to the resistor;  $N$  - number of turns of spiral;  $t$  - space of the cutting of spiral;  $l$  - length of the foundation of the resistor between the contact caps/hoods.

With the spiral-shaped resistive element/cell strongly grows/rises the shunting effect of the conductivity of insulating foundation  $R'_n$  and protective coating  $R'_n$ , which prove to be concentrated in the short sections between the turns of the conducting spiral. The picture of the distribution of field lines between the adjacent turns of the conducting spiral of thin-film resistor is shown in Fig. 2.4b.

Taking into account the special features/peculiarities of radiation effect examined the equivalent schematic of the resistor (see Fig. 2.2a) at the moment of acting the impulse/momentum/pulse of radiation takes the form, shown in Fig. 2.5. In this diagram they are absent contact resistance  $R_k$ , since  $R_k \ll R_n$ , and the element/cell, which considers a change in the conductivity of film. An increase of

carrier concentration in the resistive film under the effect of the ionizing radiations/emissions cannot substantially affect the value of its conductivity, since the latter is sufficiently great under the normal conditions (before the irradiation).

The values of backs-out resistor, caused by current leak due to the ionization, can be determined from the following considerations. Knowing the distributions of the electric field between the outputs of resistor and between the adjacent turns of the conducting spiral, we will consider ionizing currents as stray currents in the parallel-plate capacitors, facings of which are the symmetrical pairs of surface elements (be it resistive layer, foundation or the outputs of the resistor Fig. 2.4b). The distance between the facings is taken by the equal to the length of the center line of electric intensity, i.e. the line, which corresponds to the vector of intensity/strength, which emerges from the center of surface element. The full current of leak/leakage is designed as the sum of the currents, which flow from each area/site.

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The value of the resistor/resistance of shunt  $R'_{sh}$ , caused by an increase in the conductivity of the material of the foundation of resistor, can be calculated by the formula

$$\frac{1}{R'_{n. \omega}} = \sigma' S \sum_{i=1}^n \frac{1}{d_i}, \quad (2.7)$$

where  $\sigma'$  - radiation electrical conductivity of the material of the foundation of resistor;  $S$  - area of surface element;  $d$  - length of the center line of the strength of field in the material of the foundation between two symmetrical surface elements;  $n$  - number of surface elements.

The resistor/resistance of shunt  $R'_{n. \omega}$ , caused by an increase in the conductivity of the material of protective coating, is expressed

$$\frac{1}{R'_{n. \omega}} = \sigma'' \frac{\pi D l h}{a t}, \quad (2.8)$$

where  $\sigma''$  - radiation electrical conductivity of the material of protective coating;  $a$  - distance between the adjacent turns of the conducting spiral;  $t$  - space of the cutting of the conducting spiral;  $D$  and  $l$  - diameter and the length of the foundation of resistor respectively;  $h$  - thickness of protective coating.

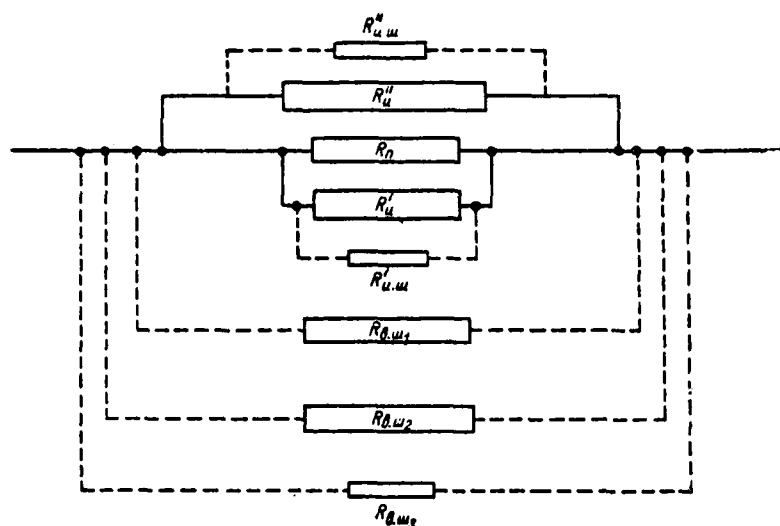


Fig. 2.5. Equivalent schematic of constant tape/film high-impedance resistor at moment of acting  $\gamma$ -radiation:  $R_n$  - resistor/resistance of conducting film;  $R'_n$  - base resistance of resistor;  $R''_n$  - resistor/resistance of protective coating of resistor;  $R'_{n,u}$  and  $R''_{n,u}$  - resistor/resistance of shunts due to current leak in interturn gap, caused by increase of conductivity of materials of foundation of resistor and protective coating respectively;  $R_{b,u1}$  - resistor/resistance of shunt, caused by leak/leakage by ionized air between outputs of resistor;  $R_{b,u2}$  - resistor/resistance of shunt due to current leak in interturn gap through thickness of protective coating and ionized air;  $R_{b,u3}$  - resistor/resistance of shunt, caused by current leak between contact caps/hoods due to increase in conductivity of protective coating and air.

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The value of the resistor/resistance of shunt  $R_{n.ш.}$  due to the current leak between the conclusions/outputs by ionized air

$$\frac{1}{R_{n.ш.}} = A' S_1 P_y^\Delta \sum_{i=1}^n \frac{1}{d_i}, \quad (2.9)$$

where  $A'$  and  $\Delta$  - coefficients ( $A' \approx 5.6 \cdot 10^{10}$ ;  $\Delta < 1$ );  $S_1$  - area of surface element;  $d$  - length of the center line of the strength of field in air between two symmetrical surface elements;  $n$  - number of surface elements.

Resistor/resistance of shunt  $R_{n.ш.}$  due to the current leak in the interturn gap through thickness of protective coating and ionized air

$$R_{n.ш.} = \frac{A'}{S P_y^\Delta \sum_{i=1}^n \frac{1}{d_i}} + \frac{4ht}{\pi D l \sigma'' (t-a)}. \quad (2.10)$$

The resistor/resistance of the shunt, caused by current leak between the contact caps/hoods due to an increase in the conductivity of protective coating and air

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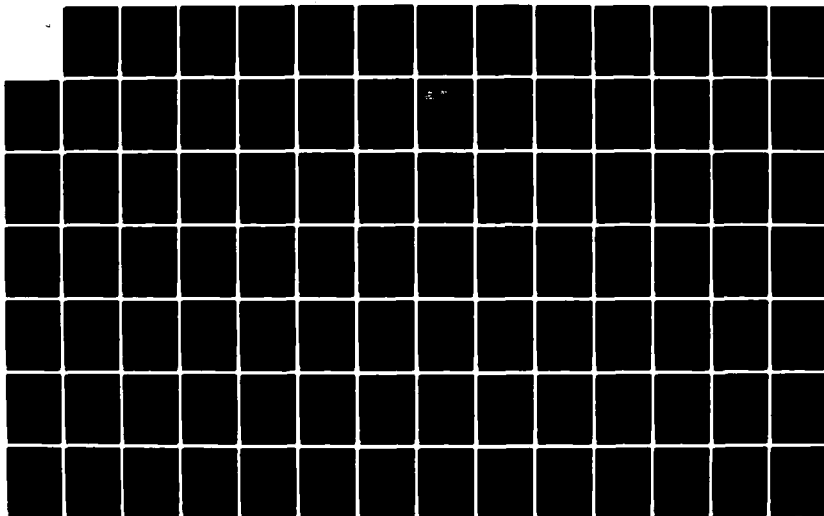
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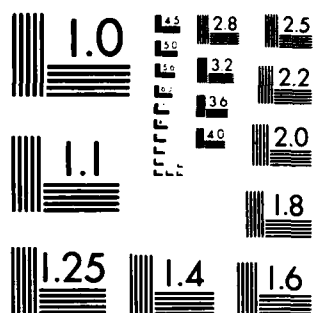
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$$R_{\text{с. ш.}} = A' \frac{l}{S_2} + \frac{h}{\pi D \sigma'' (c + b)}, \quad (2.11)$$

where  $S_2$  - area of the end/face of contact cap/hood;  $c$  - thickness of the end/face of contact cap/hood;  $b$  - length of contact cap/hood.

Expression for resisting the complete shunt, which appears at the moment of the effect of radiation/emission for the resistor with the spiral cutting, takes the form

$$\frac{1}{R_{\text{сбш. ш.}}} = \frac{1}{R'_{\text{ш. ш.}}} + \frac{1}{R''_{\text{ш. ш.}}} + \frac{1}{R_{\text{с. ш.}}} + \frac{1}{R_{\text{с. ш.}}} + \frac{1}{R_{\text{с. ш.}}}. \quad (2.12)$$

where  $R'_{\text{ш. ш.}}$ ,  $R''_{\text{ш. ш.}}$ ,  $R_{\text{с. ш.}}$ ,  $R_{\text{с. ш.}}$ ,  $R_{\text{с. ш.}}$  are determined from formulas (2.7)-(2.11).

The values of shunts for the high-impedance carbonic resistor of spiral construction/design with the nominal resistor/resistance to  $\sim 1 \text{ M}\Omega$  and with a dissipated power of 0.5 W are given in Table 2.4.

Thus, the value of the resistor/resistance of the complete shunt, which appears in high-impedance resistor under the effect of the ionizing radiation/emission in the range of the powers of exposure doses to  $10^7 \text{ r/s}$ , in essence is determined by the value of resistor/resistance  $R_{\text{с. ш.}}$  due to the current leak in the interturn gap through thickness of protective coating and ionized air.

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Since air resistance in this case is considerably lower than the strength of materials of coating, the value of the resistor/resistance of shunt  $R_{s.w.}$  can be with a precision/accuracy sufficient for the practice determined from the equation

$$R_w = \frac{l}{\pi D l} \cdot \frac{1}{1-a} \cdot \frac{4h}{A p_v^{\Delta}} \quad (2.13)$$

where  $A$  and  $\Delta$  - coefficients, which characterize a change in the electrical conductivity of the material of the protective coating (see Table 1.4).

The corresponding value of a relative change in the ohmic resistance of tape/film spiral resistor can be calculated by the formula

$$\frac{\Delta R}{R_0} = 1 - \frac{1}{1 - \frac{R_0}{R_w}} \quad (2.14)$$

or

$$\frac{\Delta R}{R_0} = 1 - \frac{1}{1 + R_s \left( \frac{\pi D l}{l} \right)^2 A p_v^{\Delta} \frac{1}{4h}} \quad (2.15)$$

where  $R_0$  - resistor/resistance of resistor to the irradiation, the ohms;  $\Delta R$  - value of a change of the ohmic resistance of resistor in the process of irradiation, ohms;  $R_s$  - resistor/resistance of the square of resistive film,  $\Omega/\text{cm}^2$ .

The value of back-out resistor is directly proportional to the thickness of protective coating. Therefore by most rational and effective safety method of resistors from the effect of high intensity radiation/emission is an increase in the thickness of protective coating via the pressing of separate samples/specimens or their filling in the composition of diagrams and units of equipment. It suffices to say that in certain cases an increase of the thickness of coating approximately/exemplarily 10 times during irradiation with a power of the exposure dose of  $10^7$  r/s makes it possible to decrease a change of resisting the resistor 6-8 times.

Table 2.4.

Computed values of the resistor/resistance of shunts during the gamma-irradiation with different powers of exposure dose.

(1) $\gamma$ , p,сек	(2) Сопроотивление шунта, Мом					
	$R_{н. ш.}$	$R_{н. ш.}$	$R_{в. ш.}$	$R_{в. ш.}$	$R_{в. ш.}$	$R_{общ. ш}$
$10^4$	8600	3290	435	39,6	3500	37
$10^7$	1000	488	138	6,3	1110	6,03
$10^8$	137	64	43,5	0,96	350	0,93
$10^9$	18	8,5	13,8	0,18	111	0,17

Key: (1). r/s. (2). Resistor/resistance of shunt, MΩ.

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Certain effect of a decrease in the effect of ionization can be achieved/reached by the selection of the optimum values of the space of cutting and width of interturn gap/interval, and also by use/application for the protective coatings of the materials, whose conductivity is less subjected to radiation effect [materials with the low values of coefficients of  $A$  and  $\Delta$ ; see formula (1.10)].

In the equipment, intended for the work under the conditions for high intensity radiations/emissions, it is possible to recommend

use/application on the possibility of comparatively low-resistance resistors ( $R_{nom} < 10$  kilohm). High-impedance resistors to admissibly utilize only in the pressing and the filling. For the resistors with a nominal resistor/resistance of more than  $10\text{ M}\Omega$  in the case of the impossibility of the filling of entire diagram it is necessary except pressing to provide for the appropriate unsoldering so that the outputs of resistor would be maximally distant from each other, in this case conclusions/outputs and the places of soldering should be covered insulating varnishes or other protective materials.

### 2.3. Irreversible changes in the parameters of resistors.

During irradiation of resistors together with the temporary/time (reversible) changes in the parameters, caused by ionizing processes and processes of radiation heating, can occur the irreversible (residual/remanent) changes. Residual/remanent changes in parameters and operating characteristics of resistors are connected in essence with the damage of the structure of the materials of conducting elements and dielectric materials, utilized as the foundations, frameworks/bodies, protective coatings, pressing, etc.

Among the materials, utilized in the constructions/designs of resistors, are most sensitive to  $\gamma$ - and neutron radiations/emissions organic matter and polymers (varnishes, enamels, bonding agents,

compounds, etc.), materials, which contain in their composition of  $B^{10}$  (conducting film of boron-carbon resistors, some types of borate glass, utilized for the foundations and the protective coatings), and also semiconductor materials (conducting film of metal-oxide resistors, etc.).

As it was noted, the majority of the reactions in the organic and polymeric matter (which call residual/remanent changes in their physicochemical properties) regardless of the fact, they are induced by fast electrons, X-ray or by  $\gamma$ -radiations or by the mixed  $\gamma$ -neutron radiation/emission, it depends, first of all, on the general/common/total absorbed energy, sometimes from the intensity of radiation/emission and it is very rare from the type of radiation/emission or radiation source.

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Residual/remanent changes in the fundamental characteristics of the boron-containing substances are caused in essence by the processes of interaction of thermal neutrons with the atoms of the isotope of boron  $B^{10}$ . The value of these changes is proportional to the flow value of thermal neutrons.

As a result of interaction of fast neutrons with the atoms of

crystal lattice of semiconductor materials occurs the formation/education of structural imperfections, which are retained during the long time and are caused stable changes in the physicochemical characteristics of these materials and are considerable, the greater the value of integral fast neutron flux.

Thus, residual/remanent changes in the parameters of resistors are caused by stable changes in the characteristics of materials, used in their constructions/designs, and depend both on the value of the total absorbed dose of  $\gamma$ -radiation and on the values of the neutron fluxes and their energy spectrum.

The radiation damage of the structure of structural materials can also in a number of cases lead to a decrease in the stability of fundamental operating characteristics of the resistors: the service lives and storage, thermo- and hydrostability, mechanical and dielectric strength, reliability.

Some data are given below with respect to residual/remanent changes in the parameters of the constant and variable/alternating resistors of different forms and standard ratings.

Tape/film carbonic and boron-carbon resistors. The conducting layer of tape/film carbonic resistors is formed by the pyrolytic

deposition of carbon to the foundations from the steatite or the glass. These resistors are manufactured two types: usual performance and moisture-proof. The conducting film of conventionally configured resistors is shielded only by coatings (varnish, enamel), in the resistors of the increased hydrostability is provided for supplementary pressing by epoxy resin or the sealing of resistors into the ceramic jackets.

Among the materials, utilized in the construction/design of carbonic resistors, the conducting layer (pyrolytic carbon) and the organic materials of protective coating are most subjected to the action of penetrating radiation. Characteristic for the tape/film carbonic resistors in the process of prolonged  $\gamma$ - and neutron irradiation is the gradual insignificant increase in the ohmic resistance, apparently connected with the decrease of the fundamental conductivity of pyrolytic carbon as a result of forming the structural imperfections [36] and chemical changes in the conducting film as a result of the gas absorption and oxidation. Fig. 2.6 illustrates character and value of a relative change in the ohmic resistance of tape/film carbonic resistors with nominal resistors/resistances of from 100 ohms to 1 M $\Omega$  during irradiation by the mixed  $\gamma$ -neutron flow (the cumulative dose of  $\gamma$ -radiation approximately/exemplarily  $4.5 \cdot 10^4$  p). Resistors were irradiated without the electrical load, the temperature in the process of

irradiation did not exceed +70°C.

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In this case was not observed noticeable disagreement in the character and the values of a change of resisting the resistors of different ratings. Residual/remanent changes in the resistor/resistance after irradiation did not exceed  $\pm 1\%$ .

Supply to the tape/film carbonic resistors of nominal electrical load, as a rule, leads to an increase in the relative change of the ohmic resistance in the process of irradiation, the value of residual/remanent changes also somewhat increases, but it does not exceed the limits of 2%.

The subsequent tests of the irradiated samples/specimens of tape/film carbonic resistors for the cyclic effect of the increased humidity and temperature (15 cycles) <sup>1</sup> showed that the irradiation to neutron fluxes indicated above and doses of  $\gamma$ -radiation virtually does not affect their hydrostability.

FOOTNOTE <sup>1</sup>. Experimental cycle includes three stages: the I stage: relative humidity in the chamber/camera is raised to 90-95%, in this case the temperature increases to +65° C; the II stage: the

conditions, achieved/reached in the I stage, are maintained/withstood during the III stage: temperature descends to that surrounding, relative humidity is retained at the level 90-95%, the measurement of the parameters of resistors is made. ENDFOOTNOTE.

Table 2.5.

Approximate value of a residual/remanent change of resisting the tape/film carbonic resistors after irradiation by fast neutron flux  $10^{11}$  neutrons/cm<sup>2</sup> (associated exposure dose of  $\gamma$ -radiation  $5 \cdot 10^6$  p).

(1) Номинальное сопротивление резистора, ом	(2) Изменение сопротивления $\Delta R/R$ образцов, %		
	(3) облученных	(4) контрольных	(5) облученных после циклического увлажнения
100	+0,3	+0,1	<2
$250 \cdot 10^3$	+0,6	+0,1	<2
$10^6$	-0,5	+0,1	<3

Key: (1). Nominal resistor/resistance of resistor, ohms. (2). Change of resisting  $\Delta R/R$  samples/specimens, %. (3). irradiated. (4). control rooms. (5). irradiated after cyclic moistening.

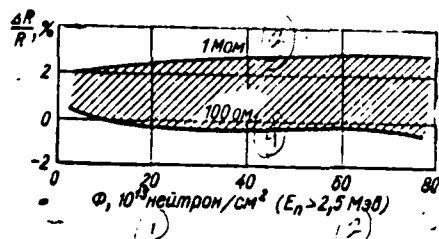


Fig. 2.6. Change of resisting tape/film carbonic resistors in process of prolonged irradiation by mixed  $\gamma$ -neutron flow.

Key: (1). neutrons/cm<sup>2</sup>. (2). MeV. (3). MΩ. (4). ohm.

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Table 2.5 gives the data about residual/remanent changes of resisting the irradiated and control (not exposed to irradiation, but located at a temperature, which corresponds to the temperature in the reactor channel) samples/specimens of tape/film carbonic resistors. The data about changes of resisting the irradiated samples/specimens after prolonged cyclic moistening are here cited.

The tape/film carbonic resistors of the increased hydrostability, which have organosilicon protective coating and supplementary pressing, with nominal resistors/resistances to 1

kilohm and 1 M $\Omega$  were exposed to irradiation on  $\gamma$ -source Co<sup>60</sup> with a power of the exposure dose of the  $\gamma$ -radiation of  $5.9 \cdot 10^5$  p/h up to the cumulative doses from  $10^4$  to  $7.2 \cdot 10^5$  p [37]. Resistors tested under the nominal electrical load and without the load (passively). The parameters of resistors were checked before and after irradiation.

Tables 2.6 and 2.7 give the average/mean values of the temperature specific resistance and emf of the noises of the control and irradiated by different doses samples/specimens of resistors.

Table 2.6.

Values TKS of tape/film carbonic resistors after the effect of  $\gamma$ -radiation.

(1) Номинальное сопротивление резистора, ом	(2) Экспозиционная доза $\gamma$ -излучения, $10^7$ р	(3) Диапазон разброса значений ТКС образцов, $10^{-6}$ на $1^\circ\text{C}$	
		(4) облученных	(5) контрольных
$10^6$	7,0	-332 — -267	-354 — -268
$10^5$	2,3 2,3 7,0	-239 — -213 -241 — -212 -249 — -214	-246 — -219

Key: (1). Nominal resistor/resistance of resistor, ohms. (2).

Exposure dose of  $\gamma$ -radiation,  $10^7$  p. (3). Range of scatter of values

TKS of samples/specimens,  $10^{-6}$  on  $1^\circ\text{C}$ . (4). Irradiated. (5). Control rooms.

Table 2.7.

Value emf of the noises of tape/film carbonic resistors after the effect of  $\gamma$ -radiation.

(1) Номиналь- ное сопро- тивление резистора, ом	(2) Экспози- ционная доза $\gamma$ -из- лучения, $10^7$ р	Э. д. с. шумов у образцов, мВ/с					
		(3) облученных			(7) контрольных		
		(4) средний	(5) минималъ- ный	(6) макси- мальный	(4) средний	(5) минималъ- ный	(6) макси- мальный
10 <sup>6</sup>	0,48	0,74	0,68	0,80	0,39	0,28	0,45
	3,3	0,33	0,24	0,45			
	7,2	0,83	0,30	1,60			
10 <sup>5</sup>	0,24	0,068	0,053	0,078	0,041	0,035	0,043
	7,2	0,046	0,041	0,065			

Key: (1). Nominal resistor/resistance of resistor, ohms. (2). Exposure dose of  $\gamma$ -radiation,  $10^7$  p. (3). irradiated. (4). average/mean. (5). minimum. (6). maximum. (7). control rooms.

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Fig. 2.7 gives the data, which characterize the stability of the fundamental operating parameters of these resistors after irradiation to doses, indicated above. In the process and after aging test under the nominal electrical load at a maximum temperature on it was observed essential difference in the behavior of the irradiated and control samples/specimens. At the same time during the tests for cyclic effect of temperatures and increased humidity certain deterioration in the stability of the resistor/resistance of these resistors was fixed/recorded.

Are not discovered any noticeable changes in the chemical composition and hardness of the materials, used in the construction/design, after gamma-irradiation by cumulative dose  $10^4$  p. Microphotography/microphotographs given in Fig. 2.8 of the structure of the cross sections of these resistors also do not detect essential difference in the structure of the materials of the irradiated and control samples/specimens.

Somewhat different character of a change of the

resistor/resistance in the process of prolonged  $\gamma$ - and neutron irradiation is observed in the tape/film boron-carbon resistors. Their construction/design is analogous to the construction/design of tape/film carbonic resistors with the only difference that the boron is introduced into the composition of the conducting film for the stabilization of the electrical parameters. Fig. 2.9 shows the characteristic form of the dependence of the value of a change of resisting the boron-carbon resistors from the neutron flux.

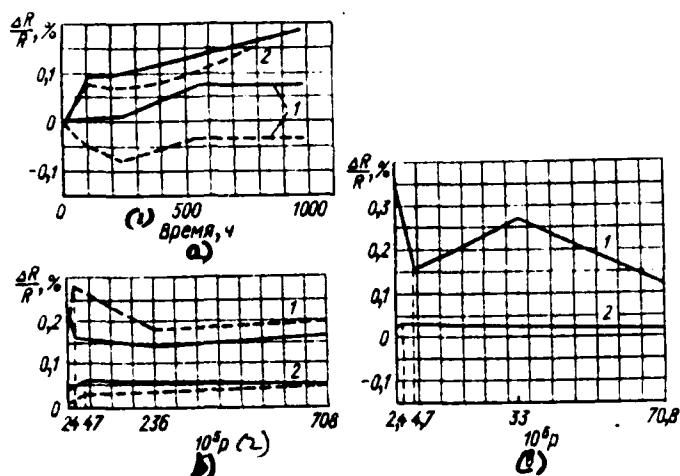


Fig. 2.7. Change of resistance of the irradiated in the exposure dose  $7.2 \cdot 10^7$  R (unbroken curves) and control (dotted curves) samples/specimens of the pressed tape/film carbonic resistors in the process of testing for aging (a) with the nominal electrical load and maximum operating temperature, and also on the effect of the increased humidity (b) and the cyclic effect of temperatures (c): 1 - 1 MΩ; 2 - 1 kilohm.

Key: (1). Time, h. (2). R.

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The irradiation of resistors was conducted without the electrical load, the temperature in the reactor channel oscillated in limits of 30-90°C. For the comparison the same figure shows a change of

resisting the tape/film carbonic resistors with the nominal resistor/resistance of 100 ohms. If the resistor/resistance of boron-carbon high-impedance and carbonic low-resistance resistors virtually does not change during irradiation to the integral thermal neutron fluxes  $1.5 \cdot 10^{14}$  neutrons/cm<sup>2</sup>, then in boron-carbon resistors with the nominal resistors/resistances to 100 kilohm and less occurs a considerable increase in the resistor/resistance.

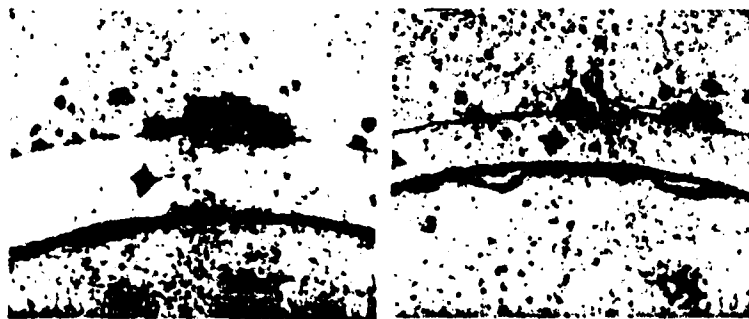


Fig. 2.8. Microstructure of the cross section of that irradiated (a) at the exposure dose of  $\gamma$ -radiation  $7.2 \cdot 10^7$  R and control (b) of the samples/specimens of the pressed tape/film carbonic resistors

(magnification  $\times 125$ ).

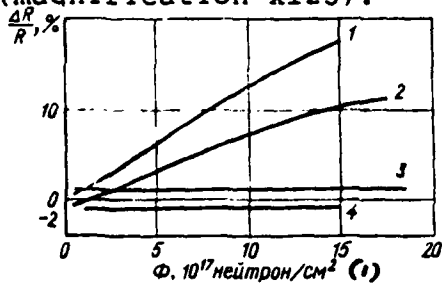


Fig. 2.9. Change of resisting tape/film boron-carbon resistors in dependence on thermal neutron flux: 1 - 100 ohms; 2 - 100 kilohm; 3 - 1 MΩ; 4 - 100 ohms (tape/film carbonic resistors).

Key: (1). Neutrons/cm<sup>2</sup>.

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These changes, as a rule, carry stable character and are retained after the cessation/discontinuation of irradiation. The reason for

these changes - damage of the structure of the material of the conducting film, in which is included isotope  $B^{10}$ , which possesses large interaction cross section with the thermal neutrons (see Chapter 1). The higher the concentration  $B^{10}$  in the composition of boron-carbon film, the more considerable the effect of structural disturbances/breakdowns on the value of the corresponding change in the ohmic resistance of resistors. This can explain the difference in the behavior of low-resistance and high-impedance boron-carbon resistors.

An increase in the coefficient of hydrostability (tentatively two times in comparison with the control samples/specimens) is observed also together with residual/remanent changes in the resistor/resistance after prolonged irradiation in tape/film boron-carbon resistors.

Since the boron-carbon resistors are applied in the equipment as stable of the increased precision/accuracy, changes indicated above of their parameters as a result of irradiation can lead to the disturbance/breakdown of the normal functioning of equipment.

Constant composite resistors. The solid semi-conducting materials, obtained from the mechanical mixtures of powder-like semiconductors and metals with the dielectric, are the conducting

element of composite resistors. Carbon in the form of carbon black and graphite predominantly is utilized as the conducting components (in particular in the compositions with the organic ones by bonding agent). The varnish-film/lacquer-film and volumetric constructions/designs of composite resistors are most widely used.

The characteristic effect of effect of  $\gamma$ - and neutron radiations/emissions on the composite carbonic/carbon resistors is the gradual decrease of resistor/resistance in the course of time of irradiation. Fig. 2.10 shows the dependences of a change of resisting the tape/film carbonic/carbon composite resistors of different ratings on the neutron flux [52]. Resistors with the identical nominal resistors/resistances and the powers of the scattering, prepared by different suppliers (with the possible differences in technology), can have different stability to the effect of irradiation.

The prolonged irradiation of constant tape/film composite resistors on the cobalt source to the cumulative doses of  $\gamma$ -radiation  $1.6 \cdot 10^5$  R also causes the decrease of ohmic resistance (Fig. 2.11). The values of residual/remanent changes of resisting these resistors after prolonged  $\gamma$ -neutron irradiation to the integral thermal neutron fluxes of order  $10^{17}$  neutrons/cm<sup>2</sup> (associated doses of  $\gamma$ -radiation  $10^5$  R) and after irradiation on the cobalt source to the cumulative

doses of approximately  $10^4$  R have the comparable value and comprise on the average from 4 to 10% of initial value [10].

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The character of a change of resisting the volumetric composite resistors is analogous observed for the tape/film composite resistors. Fig. 2.12 gives data about the effect of prolonged irradiation on the stability of the resistor/resistance of volumetric composite resistors [10].

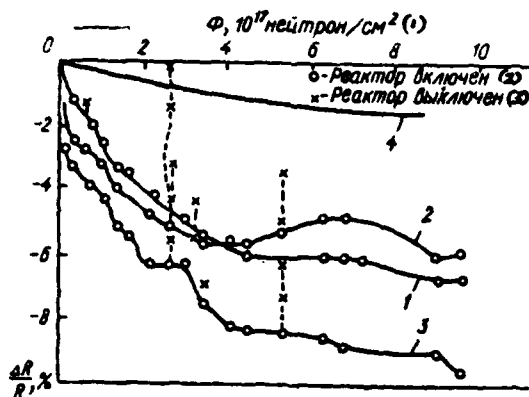


Fig. 2.10. A change of resisting the tape/film carbonic/carbon composite resistors with the nominal resistor/resistance to 1 MΩ in the process of irradiation in nuclear reactor: 1 - firm Allen-Bradley; 2 - firm Stackpole; 3 - firm Sper; 4 - 100 ohms firm Allen-Bradley.

Key: (1). neutrons/cm². (2). Reactor is connected. (3). Reactor is switched off.

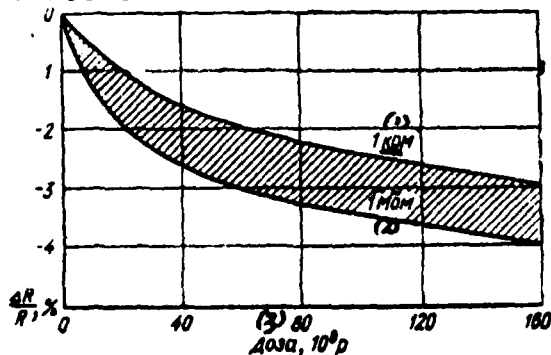


Fig. 2.11. Change of resisting tape/film composite resistors in process of irradiation on cobalt source.

Key: (1). kilohm. (2). mΩ. (3). Dose, 10⁴ R.

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Samples/specimens with nominal resistors/resistances of from 100 ohms to 1 M $\Omega$  without the electrical load tested, the density of the flow of thermal and fast neutrons respectively composed  $1.4 \cdot 10^{12}$  neutrons/cm<sup>2</sup>·s and  $2.3 \cdot 10^7$  neutron(s)/cm<sup>2</sup>·s, rate of the dose of  $\gamma$ -radiation  $4.3 \cdot 10^3$  R/s.

Table 2.8 gives the data about residual/remanent changes of resisting the volumetric composite resistors after irradiation.

Prolonged irradiation to those indicated in Table 2.8 flows and doses of  $\gamma$ -radiation leads to a decrease in the hydrostability of volumetric and especially tape/film composite resistors. A considerable increase in the ohmic resistance (Table 2.9) occurs as a result of the cyclic effect of the increased humidity in the irradiated samples/specimens.

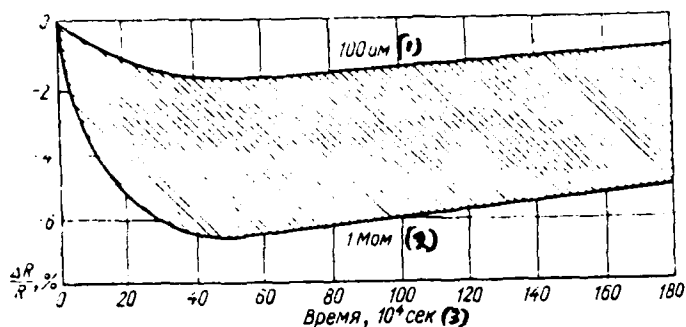


Fig. 2.12. Change of resisting the volumetric composite resistors in the process of irradiation in nuclear reactor.

Key: (1). ohm. (2). MΩ. (3). Time,  $10^4$  s.

Table 2.8. Residual changes of resistance of volumetric composite resistors after irradiation by fast neutron flux  $\sim 10^{14}$  neutrons/cm<sup>2</sup>. (associated exposure dose of  $\gamma$ -radiation  $\sim 10^6$  R).

(1) Номинальное сопротивление резистора, Ом	(2) Ориентировочное изменение сопротивления $\Delta R/R$ образца, %	
	(3) облученного	(4) контрольного
$10^2$	-2	-0,1
$10^3$	-4	-0,1
$1,2 \cdot 10^4$	-10	+0,3
$10^5$	-9	+0,8

Key: (1). Nominal resistor/resistance of resistor, ohms. (2). Tentative change of resisting  $\Delta R/R$  sample/specimen, %. (3). irradiated. (4). control room.

The irreversible damage of the structure of the organic materials, used as the bonding agents in the conducting composition, can be the reason for the observed residual/remanent changes of the parameters of composite resistors as a result of irradiation.

Tape/film metallized resistors. The construction/design of metal-film resistors is analogous to the construction/design of tape/film carbonic and composite resistors. Only as the conducting elements of these resistors are utilized the thin films of special alloys or metals, precipitated to the insulating foundation by different methods, among which most extensively is used the method of thermal vacuum evaporation. For the foundations of metal-film resistors are utilized, as a rule, inorganic materials, the ceramics, glass, etc. Acrylate and glassy materials are utilized as the protective coatings in the metal-film resistors. Supplementary pressing with the use/application of epoxy resins is provided for sometimes.

In the stability of fundamental characteristics these resistors approach wire precision resistors, which, first of all, depends on the used in the construction/design of resistors materials, which possess the increased heat resistance together with the sufficiently

high stability. This fact significantly determines the stability of metal-film resistors to  $\gamma$ - and neutron to radiations/emissions.

Thus, during irradiation of metal-film resistors with different nominal resistors/resistances in the reactor channel to the fast neutron fluxes  $1.3 \cdot 10^{14}$  neutrons/cm<sup>2</sup> (respectively, thermal -  $2 \cdot 10^{14}$  neutrons/cm<sup>2</sup>, epithermal -  $1.9 \cdot 10^{14}$  neutrons/cm<sup>2</sup>) and the exposure doses of  $\gamma$ -radiation  $1.6 \cdot 10^6$  R was observed a gradual increase in the ohmic resistance to +3.5%, in this case residual/remanent changes in the resistor/resistance did not exceed +1.5% (Fig. 2.13) [10].

Table 2.9. Residual/remanent changes of resisting the irradiated (dose of  $\gamma$ -radiation  $\sim 10^6$  R) samples/specimens of composite resistors after the effect of the increased humidity.

Номинальное сопротивление резистора, ом (1)	Изменения сопротивления резисторов $\Delta R/R$ , % (2)	
	пленочных (3)	(4) объемных
$10^3$	-1 (5-27)	+5
$10^4$	+ (37-58)	-
$1,2 \cdot 10^5$	---	+12
$10^6$	+ (26-30)	-

Key: (1). Nominal resistor/resistance of resistor, ohms. (2). Changes of resisting resistors  $\Delta R/R$ , %. (3). tape/film. (4). volumetric.

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The pressed metal-film resistors of the type RN65C with nominal resistors/resistances to 1 kilohm and 750 kilohm (conducting layer - the film of Nichrome) were exposed to irradiation on the cobalt  $\gamma$ -source with a power of the exposure dose of the  $\gamma$ -radiation of  $5.9 \cdot 10^5$  R/h up to the total exposure doses from  $10^4$  to  $7.2 \cdot 10^7$  R [37]. Resistors tested under the nominal electrical load and without the load (passively). The parameters of resistors were checked before and after irradiation. Tables 2.10 and 2.11 give the average/mean values of the temperature specific resistance and emf of the noises of the control and irradiated at different doses samples/specimens of

resistors.

After irradiation to the exposure doses of  $\gamma$ -radiation indicated metal-film resistors together with the control samples/specimens were subjected to tests for effect of different operating factors: the increased humidity, the cyclic effect of temperatures, the prolonged effect of nominal electrical load at maximum operating temperature. Fig. 2.14 shows a change of resisting the resistors as a result of these effects.

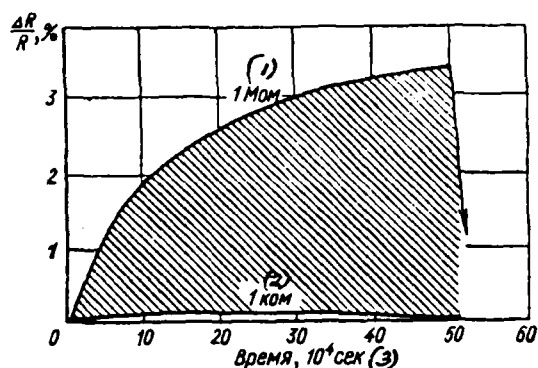


Fig. 2.13. Change of resisting the metal-film resistors in the process of irradiation by a  $\gamma$ -neutron flow in nuclear reactor.

Key: (1). MΩ. (2). Kiloohm. (3). Time,  $10^4$  s.

Table 2.10. Average/mean values of TCR of metal-film resistors of the type RN65C after prolonged gamma-irradiation.

(1) Номинальное сопротивление резистора, $10^4$ ом	(2) Экспозиционная доза $\gamma$ -излучения, $10^7$ p	(3) Значения ТКС образцов (миллионные доли на $1^\circ\text{C}$ )	
		(4) облученных	(5) контрольных
1	7,0	-37 + -17	-38 + -16
750	2,3	-15 + 8	
	3,3	11 + 34	-9 + 35
	7,0	-18 + 27	

Key: (1). Nominal resistor/resistance of resistor,  $10^4$  ohms. (2).

Exposure dose of  $\gamma$ -radiation,  $10^7$  p. (3). Values of TCR of samples/specimens (millionth portions on  $1^\circ\text{C}$ ). (4). irradiated. (5). control.

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During the study of these resistors were not discovered any noticeable changes in the chemical composition, structure and hardness of the materials, used in their construction/design.

Metal-oxide resistors. The greatest practical use/application obtained the resistors on the base of the dioxide of tin ( $\text{SnO}_2$ ), and also the resistors, the fundamental components of film of which are  $\text{SnO}_2$ ,  $\text{Sb}_2\text{O}_3$ ,  $\text{ZnO}$ . Oxide films are deposited to the ceramic or glass foundations. Epoxy varnishes and silicon enamels are utilized as the protective coatings. These resistors are characterized by the increased heat resistance (to  $+200^\circ\text{C}$ ) and by the sufficiently high stability of the parameters.

Table 2.11. Averaged values of emf of the noises of metal-film resistors of the type RN65C after prolonged gamma-irradiation.

Номиналь- ное сопротив- ление резистора, $10^3 \text{ ом}$	Экспози- ционная доза $\gamma$ -из- лучения, $10^4 \text{ р}$	(3) Значения э. д. с. шумов для образцов, $\mu\text{в/в}$					
		(4) облученных			(5) контрольных		
		среднее (6)	минималь- ное (7)	макси- мальное (8)	среднее (6)	минималь- ное (7)	макси- мальное (8)
1	2,4	0,013	0,010	0,019	0,011	0,011	0,012
750	72	0,012	0,010	0,019			
	2,4	0,022	0,012	0,026			
	72	0,052	0,010	0,125	0,06	0,012	0,14

Key: (1). Nominal resistor/resistance of resistor,  $10^3$  ohms. (2). Exposure dose of  $\gamma$ -radiation,  $10^4$  R. (3). Values of emf of noises for samples/specimens,  $\mu\text{V/V}$ . (4). irradiated. (5). control rooms. (6). average. (7). minimum. (8). maximum.

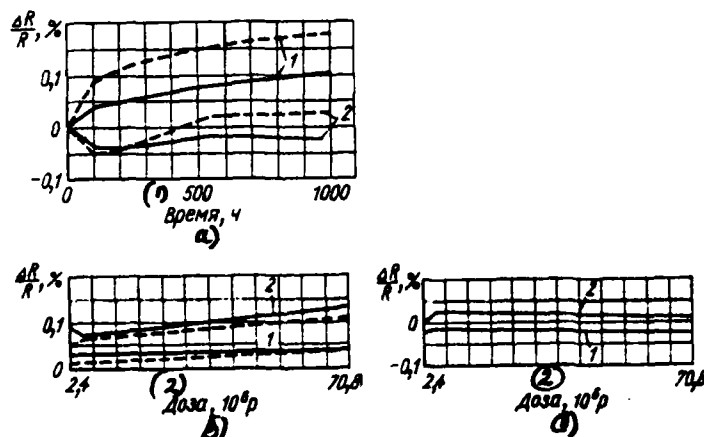


Fig. 2.14. Change of resisting irradiated in dose  $7.2 \cdot 10^4$  R (unbroken curves) of control (dotted curves) samples/specimens of metal-film resistors in process of testing for aging (a) with nominal electrical

load and maximum operating temperature, on effect of increased humidity (b) and cyclic effect of temperatures (c): 1 - 1 kilohm; 2 - 750 kilohm.

Key: (1). Time, h. (2). Dose,  $10^4$  R.

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Metal-oxide resistors in their properties and construction/design are close to the metal-film resistors. However, they are more sensitive to  $\gamma$ - and neutron radiations/emissions, than metal-film resistors.

Fig. 2.15 gives the dependences of a change in the ohmic resistance of metal-oxide resistors (content of oxide of antimony  $Sb_2O_3$ , from 0.5 to 4%) in the process of prolonged irradiation in the reactor to the neutron fluxes  $10^{14}$  neutrons/cm<sup>2</sup> ( $E_n > 0.1$  MeV), the associated dose of  $\gamma$ -radiation  $\sim 10^4$  R. The resistor/resistance of metal-oxide resistors gradually increases as a result of irradiation. With the neutron fluxes  $10^{14}$  neutrons/cm<sup>2</sup> this increase composes +10%. Changes in the resistor/resistance carry residual/remanent character and are retained after the cessation/discontinuation of irradiation.

The observed increase in the resistor/resistance is connected with the processes, which call the structural damage of the material of the conducting film, since other materials, used in the construction/design of metal-oxide resistors (glass, copper, red brass, epoxy varnish and silicon enamel) for the flows indicated and the doses are less sensitive to the effect of irradiation. The fact is that through the type of electrical conductivity the conducting film of metal-oxide resistors can be attributed to the class of semiconductor materials, whose change in the electrical conductivity occurs as a result of the onset of radiation defects. The latter are caused by interaction of fast neutrons with the atoms of crystal lattice. In this case are formed the impurity atoms and the defects of shift, which are preservable during the long time and, as a result, residual/remanent changes of resisting the resistors. The value of these changes is proportional to the flow of neutron radiation/emission and with the neutron fluxes of more than  $10^{15}$  neutrons/cm<sup>2</sup> is so great which can lead to the disturbance/breakdown of the normal functioning of the diagrams, in which are utilized metal-oxide resistors.

Wire resistors. The construction/design of wire resistors differs significantly from the construction/design of volumetric and tape/film resistors with the precipitated films. All elements of the constructions/designs of wire resistors are fulfilled from the

thermo-resistant materials, and conducting element is shielded by the dense layer of glass enamel, compound or by airtight jacket [38].

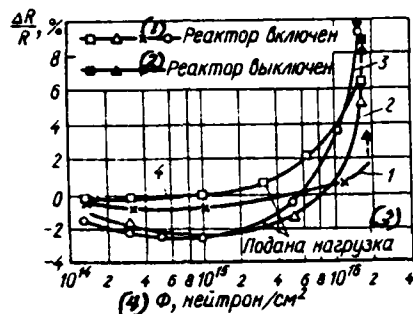


Fig. 2.15. A change of resistance of the metal-oxide resistors in the process of irradiation in reactor ( $E_n > 0.1$  MeV): 1 - 86 kilohm; 2 - 500 kilohm, 0.25 W; 3 - 500 kilohm, 0.5 W; 4 - 5.6 kilohm.

Key: (1). Reactor is connected. (2). Reactor is switched off. (3). Load is given. (4). neutrons/cm<sup>2</sup>.

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As are shown the results of a whole series of investigations, the stability of wire resistors to the effect of radiation is considerably above in comparison with other types of resistors. In the wire resistors in practice are not observed changes in the parameters during irradiation to the fast neutron fluxes  $10^{18}$  neutrons/cm<sup>2</sup>, which, obviously, is connected with the use in their constructions/designs of the materials, which possess relatively high radiation stability [52].

Non-wire variable/alternating resistors (potentiometers). Among the non-wire potentiometers the widest use received composite potentiometers with the resistive element/cell on the base of lacquer-carbon black compositions (tape/film) and potentiometers with the massive resistive element/cell (volumetric).

Prolonged  $\gamma$ -neutron irradiation, as a rule, causes residual/remanent changes in the parameters of composite potentiometers. These changes are determined in essence by the properties of the materials, used in the construction/design of potentiometers (materials of supports/bases, the connecting/cementing materials of the compositions of conducting elements and contact brushes, etc.), since in the overwhelming majority these are the polymers, which are characterized by the lowered/reduced radiation stability.

The movable current-tap contact of potentiometers even under normal conditions is the insufficiently reliable node of construction/design. Structural disturbances/breakdowns in the materials and their accompanying processes of generation of gas and especially oxidation (formation of the nonconductive oxide films on the surface of the contact brush) cause a noticeable deterioration in the conditions of contact. The contact resistance can increase so considerably sometimes (especially in low-resistance potentiometers)

which virtually causes the gaps of electrical circuit. A decrease in the insulation resistance is observed also together with changes in the contact and impedances in composite potentiometers.

As data of the tests of the irradiated samples/specimens show,  $\gamma$ -neutron irradiation leads to a decrease in their operational reliability under the influence of different climatic and mechanical factors. Are cited below data about value and character of a change in the parameters of the composite potentiometers of different constructions/designs and values of nominal resistors/resistances in the process and after  $\gamma$ -neutron irradiation.

Under the effect of  $\gamma$ -neutron radiation/emission in tape/film composite potentiometers is observed the gradual decrease of the established/installed resistor/resistance analogous how as it takes place in the process of irradiating the constant composite resistors (Fig. 2.16). Tape/film composite potentiometers with nominal resistors/resistances of from 500 ohms to 2500 kilohm without the electrical load tested.

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The measurement of the established/installed resistor/resistance of potentiometers (between the contact brush and the conclusion/output),

contact resistance and insulation resistance (between the conducting element and the housing) was made. The current-tap brush of potentiometers was set in three positions, which correspond approximately/exemplarily to the values of resistor/resistance, equal to  $1/4R_{nom}$ ,  $1/2R_{nom}$  and  $R_{nom}$ . In this case the contact resistance of high-impedance potentiometers increased not more than by 1%, in comparatively low-resistance ones (less than 50 kilohm) this increase reached 50% and more. Insulation resistance descended approximately/exemplarily to two orders. Data about residual/remanent changes impedance of these potentiometers are cited in Table 2.12. Data about residual/remanent changes of resisting the control samples/specimens here for the comparison are cited.

The prolonged action of  $\gamma$ -radiation also leads to the decrease of the resistor/resistance of tape/film potentiometers.

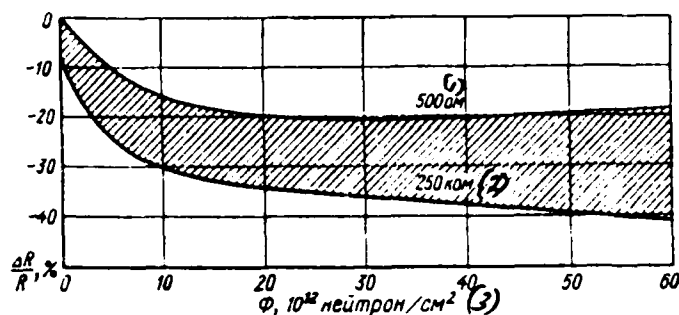


Fig. 2.16. A change of resisting the tape/film composite potentiometers in the process of irradiation by  $\gamma$ -neutron flow (dose of  $\gamma$ -radiation it reached approximately/exemplarily  $4 \cdot 10^4$  R), MeV.

Key: (1). ohm. (2). kilohm. (3). neutrons/cm<sup>2</sup>.

Table 2.12. Residual/remanent changes of resisting the composite tape/film potentiometers after irradiation to the fast neutron flux  $10^{13}$  neutrons/cm<sup>2</sup> (associated dose of  $\gamma$ -radiation  $\sim 5 \cdot 10^4$  R).

Номинальное сопротивление резистора, ом (1)	Изменения сопротивления образцов $\Delta R/R$ , % (2)	
	облученных (3)	контрольных (4)
500	-(24+26)	-(0,5+0,7)
5 000	-(19+35)	+(0,3+0,6)
50 000	-(16+39)	$\pm 0,1$

Key: (1). Nominal resistor/resistance of resistor, ohms. (2). Changes of resisting samples/specimens  $\Delta R/R$ , %. (3). irradiated. (4). control.

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Values of changes in the resistor/resistance both during irradiation on the cobalt source and during the mixed  $\gamma$ -neutron irradiation in the reactor with the comparable values of the absorbed dose of the  $\gamma$ -radiation of virtually one order.

Together with a change in the electrical characteristics  $\gamma$ -neutron irradiation causes a decrease in the hydrostability of tape/film composite potentiometers. After testing of those irradiated to flows indicated above and doses of samples/specimens by the prolonged effect of moisture the coefficient of hydrostability, which expresses a relative change of the value of resistor/resistance in the percentages during the specific period of the time of moistening under the prescribed/assigned conditions, on the average to 10% is higher than in control samples/specimens.

Composite potentiometers with the volumetric solid-pressed conducting elements are more radiation-resistant, than tape/film potentiometers [10]. In the process of the prolonged  $\gamma$ - and neutron irradiation (to the fast neutron fluxes  $4 \cdot 10^{14}$  neutrons/cm<sup>2</sup>) of volumetric potentiometers with the ratings from 25 to 2500 kilohm a

change in the total resistance (between the conclusions/outputs) does not exceed 10%. In this case the part of the potentiometers was found without the electrical load, another part - under the nominal load. The value of the established/installed resistor/resistance (between the contact brush and the conclusion/output) varies within the limits of  $\pm 4\%$ .

On the resistance to irradiation the vast class of resistors can be arranged in the order, represented in Table 2.13. Most stable to the effect of  $\gamma$ - and neutron radiations/emissions are wire resistors, then follow metal-film and tape/film carbonic resistors.

Table 2.13. Effect of irradiation on the stability of the resistors of different types.

Резисторы (1)	(2) Интегральный поток тепло- вых нейтро- нов, нейтрон/см <sup>2</sup>	(3) Необратимое изменение сопротивления резистора $\Delta R/R$ , %
Металлоокисные постоянные (4)	10 <sup>14</sup>	-2
Угольные композиционные переменные (5)	10 <sup>14</sup>	-10
Пленочные бороуглеродистые постоян- ные (6)	10 <sup>17</sup>	$\pm 1$
Металлопленочные постоянные (7)	10 <sup>14</sup>	$\pm 0,5$
Пленочные углеродистые постоянные (8)	10 <sup>14</sup>	$\pm 2$
Композиционные постоянные (9)	10 <sup>14</sup>	-12
Проволочные постоянные и переменные (10)	10 <sup>14</sup>	+1,5

Key: (1), Resistors. (2). Integral thermal neutron flux, neutrons/cm<sup>2</sup>. (3). Irreversible change of resisting resistor  $\Delta R/R$ %. (4). Metal-oxide constants. (5). Carbon composite variables. (6). Tape/film boron-carbon constants. (7). Metal-film constants. (8). Tape/film carbonic constants. (9). Composite constants. (10). Wire constants and variables.

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Constant and variable/alternating tape/film and volumetric composite resistors, and also metal-oxide and boron-carbon are very sensitive to the irradiation. In the specific flows and the doses changes in their ohmic resistance are so great that they can lead to the disturbances/breakdowns of the normal functioning of the diagrams, in

which they are utilized.

At the same time, this comparative evaluation of the radiation stability of different classes of resistors is very conditional, since, as noted above, for some articles the stability is determined by fast neutron flux (carbonic, metal-film, wire), for others (boron-carbon) - by thermal neutron flux, for the third (composite) - in the equal measure by fast neutron flux and with the dose of  $\gamma$ -radiation. Therefore the given comparison of the values of the irreversible changes of resisting different classes of resistors in the dependence on the thermal neutron flux rather illuminates the qualitative aspect of a question.

Since the irreversible change in the parameters of resistors at their use in the radio-electronic equipment can influence the parameters of some circuits, it is necessary to take measures for an increase in their stability for the ionizing radiations/emissions. One of the most effective means of an increase in the radiation stability both of wire and non-wire resistors is use in their constructions/designs of the materials of inorganic origin as the most resistant to the effect different forms of radiations/emissions.

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Chapter 3.

#### ACTION OF PENETRATING RADIATION ON CAPACITORS.

3.1. Design features of capacitors/condensers. Change in the properties of materials.

The fundamental element of the construction/design of capacitor/condenser - section is the system of the electrodes (facings), divided by dielectric. Metal foil (copper, aluminum) or thin layer of metal (zinc, aluminum), plotted/applied directly to the dielectric is utilized as the electrodes. As the dielectric wide acceptance received different organic (paper, synthetic films) and inorganic materials (mica, ceramics, glass ceramics).

The protection of condenser/capacitor sections from the effect of environmental factors is provided for guaranteeing the necessary stability of the characteristics of capacitors/condensers and increase in their operational reliability. Thus, for the purpose of

protection from moisture and improvement in the electrical characteristics (dielectric strength, losses, etc.) is conducted the saturation of the sections of capacitors, i.e., filling of the pores in the dielectric and of the gaps between the dielectric layers and the facings by any organic mass (paraffin, ceresin, condenser oil, octol). Furthermore, for protection from the external effects the saturated condenser/capacitor sections are placed into the metal or insulating housing of the condensed or airtight construction/design. Multiplexing is achieved by the filling of the ends/faces of the housing of capacitors by moisture-shielding compounds on the base of epoxy resins and polyesters/polyethers. Rubber packing are utilized also in a number of cases. At the same time they are applied the pressing of sections by plastics and pupation by moisture-proof compounds.

Wide acceptance received the hermetically sealed constructions/designs, which are the combination of metal with the ceramics or the glass, with the use/application of joints, connected by soft soldering (tin-lead). For the capacitors of great capacity are applied metal housing (usually steel) with the covers/caps soldered to them, in which seal in themselves the ceramic metallized insulators or special glass feedthrough insulators. Several sections, which have parallel (for an increase in the capacitance), consecutive (for an increase in the operating voltage/stress) or series-parallel

connection, can be placed in such capacitors in one housing.

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The parts of the external formulation of capacitors are very diverse; however, their effect on the characteristics is unessential. Therefore subsequently primary attention will be given to some design features of sections, since precisely this determines value and character of a change in the electrophysical characteristics of the capacitors of different types under the effect of penetrating radiation.

Paper capacitors. The sections of paper capacitors are the wound in the form of cylinder/reel paper tape together with aluminum foil. Changing width and diameter of cylinder/reel, it is possible to obtain the necessary range of the rated capacities of capacitors. The sections of the capacitors of comparatively small amount of capacitance have cylindrical form. In the capacitors with the higher values of capacitance are utilized the flat/plane sections, which initially are coiled around the circular mounts/mandrels, and then are removed/taken and are flattened.

The fundamental dielectric of paper capacitors (condenser/capacitor paper) consists of the separate filaments of

cellulose, fibrils and has porous structure. In the air-dried state condenser/capacitor paper contains by the volume 20-35% air. Furthermore, air unavoidably remains in the section of the capacitor between the separate layers of paper, and also between the paper and the foil as a result of the loose fit of layers. The presence of air considerably worsens/impairs the electrical characteristics of capacitor; therefore for an improvement in the stability of characteristics all paper capacitors are saturated with liquid, Vaseline-like or solids. The fundamental saturating masses are: condenser oil, petroleum jelly, ceresin, octol, low-molecular polyisobutylene.

In the metalized-paper capacitors the electrodes in the form of the thin layer of metal will be deposited directly to the surface of dielectric by the method of thermal vacuum evaporation. In this construction/design in principle there is no air layer between the electrodes and the dielectric. Substantial also that before the metallization the surface of paper is covered/coated with the thin layer (order of one micron) of the quick-drying ethylcellulose varnish. Varnish closes random openings/apertures in the paper, without making it possible to be formed in them for through metallic bridges in metallizing process it protects thin metal electrodes from the corrosion as a result of interaction with some containing in the paper admixtures/impurities of the type of chlorides, sulfates, etc.

Varnishing surface makes it possible to make capacitors, applying only one layer of paper tape. The gap between the layers of paper disappears in this case. The paper, covered with varnish, more badly soaks mass; therefore the effectiveness of saturation in the metalized-paper capacitors (especially single-layer) is considerably less than in the foil samples/specimens.

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Under the effect of the ionizing radiation in the cellulose, which is the fundamental component of condenser/capacitor paper, predominate the processes of destruction. A noticeable change in the degree of polymerization of cellulose begins in the dose of approximately 0.1 mrad [24]. Dose in 1 mrad leads to the gap 0.16% connections/communications between elementary components of the macromolecule of cellulose. This corresponds to the energy, which falls to the gap of the main chain, about 9 eV (for polyisobutylene analogous value equal approximately/exemplarily to 17 eV). The degree of polymerization of cellulose falls from an increase in the radiation dosage and increases the concentration of end groups. The radiolysis of cellulose leads to gas generation, whose large part hydrogen (approximately/exemplarily 87%) composes, and rest goes to carbon monoxide and dioxide [24].

The mechanical properties of cellulose (tensile strength, elongation) depend on average/mean molecular dimensions and decrease under the radiation effect. For example, dose in 30 mrad ( $\gamma$ -radiation) led to a decrease in the strength of knock to 82% and the ultimate elongation to 70% [24].

During irradiation of organic liquids with an increase in the dose intense generation of gas and increase in the viscosity/ductility/toughness usually is observed.

Film capacitors. Together with the paper capacitors wide acceptance received the capacitors with the dielectric from the films of polystyrene, teflon (polytetrafluoroethylene) of Lavsan [polyethylene terephthalate film, Soviet equivalent of Dacron] (polyethylene terephthalate) and triacetate of cellulose. Are developed and are produced also the combined capacitors, in which is utilized the combination of the layers of usual paper tape and polymer film (corresponding types of capacitors and their abbreviations they are given in the application/appendix).

The construction/design of the sections of the tape/film and combined capacitors differs little from the constructions/designs of the sections of paper and metalized-paper capacitors examined. Some special features/peculiarities are determined by structure and

properties of the utilized materials. In particular, all synthetic films are monolithic, porous. Consequently, the saturation of sections ceases to be necessary, and even if it is utilized, then the effect on capacitance value and other electrical parameters in comparison with the paper capacitors are exerted substantially less. Air between the dielectric layers and the dielectric and the foil, which unavoidably remains after the coil/winding of sections, it is driven out in film capacitors via pressing during the heat treatment. The use/application of a metallized film makes it possible to reduce the content of air in the sections of film capacitors to minimum.

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By their construction/design all purely film capacitors (especially metal-film) nearer anything approach the simplest diagram - one dielectric between two metal electrodes. Therefore in the majority of the cases for the analysis of a change in the parameters of these capacitors it is possible to utilize data with respect to a change in the characteristics of the corresponding polymeric materials.

During the effect of the penetrating radiations/emissions the structure and the mechanical properties of polymers most strongly changes. Table 3.1 gives the data about a change in the mechanical

properties of some most widely used in the capacitors polymeric materials [10].

Changes in the structure of polymers are accompanied, as a rule, by intense generation of gas. Molecular hydrogen usually composes basic part of the separated gases. Are more dangerous chlorine and fluorine, which are isolated from the chlorinated and flouridated polymers. These gases are corrosively active; therefore during the use of capacitors, which contain such polymeric materials, it is necessary to consider and to rate/estimate the possible effect of corrosion both on the elements/cells of capacitors themselves and on the elements of the construction/design of radio-electronic device/equipment, in which they are utilized.

For the teflon capacitors the weight of isolated fluorine to one gram of teflon in the first approximation, can be rated/estimated according to formula [8]  $q=3 \cdot 10^{-4} D$ , where  $D$  - absorbed radiation dosage, mrad.

Bulk of fluorine is isolated during the irradiation. After irradiation during approximately/exemplarily 30 days can continue the isolation/liberation of fluorine. A quantity of fluorine, which was isolated after irradiation, just as in the process of irradiation, is proportional to dose (in the repartitions/conversions to 200 mrad) [8].

Table 3.1. Change in the mechanical characteristics of polymeric condenser/capacitor dielectrics under the influence of the penetrating radiations/emissions.

(1) Материал	(2) Доза, при которой происходит уменьшение параметра, Мра			
	(3) прочность на разрыв, %		(4) удлинение, %	
	25	50	25	50
(5) Фторопласт-4	0,12	0,9	0,034	0,073
(6) Ацетат целлюлозы	23	33	23	33
(7) Лавсан	290	500	290	500
(8) Полистирол	3500 <sup>1</sup>	—	3500	—

Key: (1). Material. (2). Dose, in which occurs decrease of parameter, Mrad. (3). tensile strength, %. (4). elongation, %. (5). Teflon. (6). Cellulose acetate. (7). Lavsan. (8). Polystyrene.

FOOTNOTE <sup>1</sup>. With the indicated dose changes in the properties are not observed. ENDFOOTNOTE.

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Capacitors with the inorganic dielectric. This group includes the capacitors, fundamental dielectrics in which are different forms ceramicist, glass and mica. The firing or sintering of initial materials at high temperatures (500-1500°C) compulsorily is conducted

in the process of the production of glass, ceramic, glass-ceramic and glass-enamel capacitors. All organic matter completely burn as a result and remains the polycrystalline or amorphous composition, which consists in essence of oxides of different metals -  $Al_2O_3$ ,  $MgO$ ,  $SiO_2$ ,  $TiO_2$ , and the series/row of other compounds. All these substances, and also materials on their basis, are comparatively little subjected to changes in the conditions for irradiation [10]. In their radiation resistance they approach to metals. In contrast to the organic matter for these materials most important is not only the complete absorbed dose, but also integral fast neutron flux, since dose is to a considerable extent determined by  $\gamma$ -radiation, but the series/row of defects in these materials - by fast neutrons. Thermal neutrons do not usually have vital importance, if we do not examine sample/specimen activation, and only in the materials, which contain the atoms of boron (for example,  $B_2O_3$  in some forms of glass), the role of thermal neutrons can become noticeable as a result of interaction of neutrons with  $B^{10}$ . The construction/design of mica capacitors in principle differs from the construction/design of other types of capacitors with the inorganic dielectrics.

The section of mica capacitor is the mechanically compressed set/dialing of the leaflets of mica together with the foil electrodes (if is not conducted the metallization of the surface of mica). This section, just as the section of plastic capacitors, contains the

remainders/residues of air between the plates and has high hygroscopicity. These deficiencies/lacks cannot be removed by heat treatment, since mica at a high temperature is decomposed/expanded.

Therefore the sections of mica capacitors are saturated (usually with ceresine) and are placed into the special sealing housing or molded by plastic. An increase of the capacitance as a result of saturation does not exceed several percent [26].

Thus, although in the mica capacitors as the fundamental dielectric is utilized inorganic composition on the base of oxide of aluminum and silicon (mica), the presence of the organic matter, subjected to comparatively rapid changes during the effect of radiations/emissions, in principle does not make it possible to hope for the high degree of the stability of these capacitors in the large absorbed doses (even only  $\gamma$ -radiation).

Electrolytic and oxide-semiconductor capacitors.

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In the capacitors of this type the thin oxide film ( $\text{Al}_2\text{O}_3$ ,  $\text{Ta}_2\text{O}_5$ ,  $\text{Nb}_2\text{O}_5$ ), obtained in the process of production on one of the electrodes of capacitor, is fundamental dielectric. Special

electrolyte or solid semiconductor material serves as the second electrode. In usual chemical capacitors the presence of electrolyte in the liquid or pastelike state is necessary for obtaining high dielectric strength of oxide layer. Oxides of tantalum and niobium are utilized in the oxide-semiconductor capacitors (solid capacitors) as the dielectric, the role of electrolyte fulfills oxide of manganese ( $\text{MnO}_2$ ).

Electrolytes and semiconductor materials have comparatively high resistor/resistance, what is the reason for an increase of the losses in the facings and the corresponding increase in the dielectric power factor in comparison with other types of capacitors.

The sections of aluminum chemical capacitors are similar to the sections of the paper foil capacitors: oxidized anodic and cathode foils are divided by paper tape and are convoluted into the cylinder/reel. Paper in this case is utilized as the fibrous separator. During the saturation it is saturated by electrolyte. The initial components of electrolyte are boric acid, aqueous solution of ammonia, ethylene glycol, with the additions of ethyl alcohol and methylglycol [26].

Extensively are used in the radio-electronic equipment tantalum liquid capacitors with volumetrically-porous anode. The anode of

these capacitors is made by sintering the pressed billets of the tantalum powder. Since oxide of tantalum possesses high chemical stability, then the solution of sulfuric acid, which has a comparatively small specific resistor/resistance, is utilized as the working electrolyte. The sealing separator, which comes into contact with acid, is made from special acid-resistant fluororganic rubber.

During the effect of radiation/emission in the aluminum capacitors the radiolysis of electrolyte, which is accompanied by the isolation/liberation of gaseous products, occurs. The extrusion of the rubber sealing inserts and the complete depressurization of samples/specimens was observed as a result of this after irradiation in the reactor of dry aluminum chemical capacitors.

In liquid chemical capacitors with the bulk porous anode the sealing separator is least radiation-resistant element/cell. Fluororganic rubber in the doses of 20-50 Mrad loses the necessary elastic properties. As a result the acid can exceed the limits of the hermetically sealed space and cause a supplementary change in the characteristics of capacitor or even lead to the disturbance/breakdown of its efficiency. These processes can flow/occur/last, also, after the cessation/discontinuation of irradiation, especially in the presence of the vibrations or any other effects, which are accompanied by mechanical stresses (for

example, temperature cycles).

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### 3.2. Change in the capacitance of capacitors.

The dielectric constant of materials virtually does not change as a result of primary interaction of radiation/emission with the substance. Comparatively large changes in the capacitance of capacitors are connected usually with the secondary processes: by the mechanical strain of sections, by chemical processes in the dielectrics, etc. These changes most frequently are not reduced after irradiation. Their value under the specific conditions for irradiation is determined in essence by construction/design and used materials and little it depends on electrical load. The capacitors of the different types, which during the irradiation were found under the electrical load and without it, gave identical divergence with respect to capacitance value within the limits of the scatter of the obtained values.

Is not noticed any difference during irradiation on the pulse and static sources of penetrating radiation, since a change in the capacitance in essence depends on the absorbed dose of the ionizing radiation/emission. In the small doses these changes are

insignificant. For example, during irradiation by single emission impulse residual/remanent changes in the capacitance, as a rule, are within the limits measuring error or comprise the portions of percentage, since dose per pulse does not usually exceed the portion of megarad.

It must be noted that small changes in the capacitance of capacitors during the irradiation, especially in nuclear reactors, are frequently the consequence of the radiation heating of samples/specimens. Even during the well set checking of temperature during interpretation of the fundamental results of measurements they do not sometimes analyze the portion of temperature effect, carrying it to the radiation changes. As a result we have different opinions relative to the real value of a change in the capacitance of the identical samples/specimens of capacitors. Therefore during the analysis of experimental data, obtained during irradiation of capacitors, it is necessary to consider the effect of radiation heating.

At the very high radiation dose rate can occur the reversible changes in the capacitance of the capacitors, which are connected with the accumulation of space charge in the near-electrode regions or on the boundaries of the heterogeneities of fundamental dielectric. These phenomena are analogous to the processes, which

occur in the two-layered dielectric after application of voltage on the sample/specimen. Space charge is accumulated on the boundary of layers because of their different conductivity.

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As G. I. Skanavi [28] showed, this leads to the equivalent series capacitor of capacitor, whose value with direct/constant voltage is equal to

$$\frac{\Delta C}{C_0} = \frac{(\epsilon_1 \sigma_{p2} - \epsilon_2 \sigma_{p1})^2 d_1 d_2}{(d_2 \sigma_{p1} + d_1 \sigma_{p2})^2 \epsilon_1 \epsilon_2}$$

where  $\epsilon$  - relative dielectric constant;  $\sigma$  - specific conductivity;  $d$  - thickness of the layer. Indices "1" and "2" indicate the accessory/affiliation of the parameter with the appropriate layer.

With the alternating voltage the storage time of the charge of one sign is limited by half-period. In this case the charge cannot manage to be accumulated in this quantity as with direct/constant voltage. Series capacitor will be considerably less, and, the higher the frequency, the less the series capacitor. The restoration/reduction of capacitance must occur for the time, compared with the decay time in the induced current.

The measurement of residual/remanent changes in the capacitance is made in the majority of the cases at the frequency of 1 kHz. The

capacitance of chemical capacitors usually is measured at frequencies 50 or 100 Hz.

Paper capacitors. The analysis of the structure of condenser/capacitor paper, construction and technology of the production of paper capacitors makes it possible to consider that for the investigation of these samples/specimens it is possible to apply the consecutive equivalent diagram (Fig. 3.1) [26]. If we disregard/neglect for simplicity the effect of the thin layer of varnish in the metalized-paper capacitors, then the given equivalent diagram is applicable for the analysis of all types of paper capacitors, including metalized-paper ones.

For the evaluation/estimate of the dielectric constant  $\epsilon$  of a heterogeneous mixture of two components with the close values dielectric constants  $\epsilon_1, \epsilon_2$ , Lichtenecker proposed formula [28]

$$\epsilon^k = x\epsilon_1^k + (1-x)\epsilon_2^k, \quad (3.1)$$

where  $k$  - coefficient, determined by the mutual location of components.

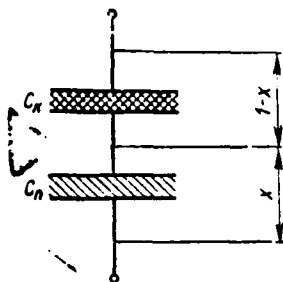


Fig. 3.1. The equivalent schematic of the saturated paper capacitor:  
 $C_K$  - the capacitance of cellulose;  $C_n$  - capacitance of the saturating mass;  $x$  - relative volume, occupied by saturation in the interelectrode gap/interval.

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In particular, for the dielectric constant of two-layered dielectric, if electric field is flatwise (consecutive equivalent diagram), coefficient  $k$  is equal minus to one. Then for  $\epsilon$  of impregnated paper we obtain

$$\epsilon = \frac{\epsilon_n \epsilon_K}{x \epsilon_K + (1-x) \epsilon_n}, \quad (3.2)$$

where  $\epsilon_K$  and  $\epsilon_n$  - dielectric constant celluloses and saturation respectively.

Under the conditions for radioactive irradiation a change in the capacitance can occur both as a result of a change in the geometric

dimensions, and as a result of a change in the dielectric constant of materials. It is possible to assume that on the basis of experimental results both these of factor affect, but in the majority of paper capacitors a change in the dielectric constant is determining. An increase in the dielectric constant cellulose and an increase of the space of the saturating mass as a result of the formation in it of bubbles of gas (frothing) occurs in the process of irradiation. Latter/last process leads to the decrease  $\epsilon$  of saturation, since the dielectric constant of gas is less than in the substance of the saturating mass. The frothing of saturation causes the extrusion of the part of the saturating mass from the section. In this case the pressure within the housing of capacitor considerably grows/rises. The developing efforts/forces are such large that was observed the extrusion of the end-type metallic covers/caps, soldered to cylindrical housing by tin solder. In the majority of cases the housing poorly breaks down itself (or at least it is disrupted its airtightness) and the saturating mass is extruded outside. The flat/plane steel housing of relatively larger sizes/dimensions acquire barrel-shaped form. Such considerable mechanical loads can lead also to certain strain of sections, especially in the large-size capacitors.

An increase in the dielectric constant cellulose occurs, probably, as a result of intense destruction and oxidizing the

cellulose, which, as already mentioned, is one of the least radiation-resistant materials and noticeably changes its properties in the doses of 1-2 Mrad.

In order to rate/estimate the degree of the effect of the processes examined on a relative change in the capacitance of paper capacitors let us turn to the results of experimental investigations.

On the graphs/curves Fig. 3.2 it is possible to isolate two characteristic regions, which are characterized by the form of the dependence of a change in the capacitance on the radiation dosage. In comparatively small doses in the different types of capacitors the decrease of capacitance is observed in essence. In the large doses the increase in the capacitance, that takes the approximately/exemplarily identical form of change, occurs. This character of dependences is connected with two mutually competing processes: by a decrease of dielectric constant saturation as a result of frothing and by an increase of the dielectric constant cellulose.

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Let us rate/estimate the effect of the process of the frothing of saturation on the decrease of capacitance of capacitors under the

influence of the ionizing radiations/emissions. The capacitance of the capacitor of the spiral construction/design

$$C = k \frac{\epsilon b L}{d}, \quad (3.3)$$

where  $k$  - constant coefficient;  $b$  and  $L$  - width and the length of facing respectively;  $d$  - thickness of dielectric.

Relative change in the capacitance

$$\frac{\Delta C}{C_0} = \frac{C}{C_0} - 1. \quad (3.4)$$

If  $k$ ,  $b$ ,  $L$  and  $d$  do not change during irradiation, then

$$\frac{\Delta C}{C_0} = \frac{\epsilon}{\epsilon_0} - 1, \quad (3.5)$$

where  $\epsilon_0$  and  $\epsilon$  - dielectric constant papers before the irradiation and during the irradiation respectively.

The gas bubbles are formed as a result of generation of gas in the saturation. We will consider that they evenly distributed by the space of the impregnating mass, since the probability of their formation/education in any place of space is identical.

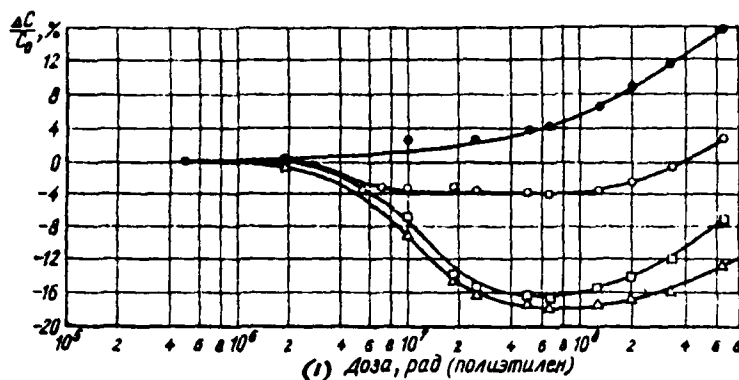


Fig. 3.2. A change in the capacitance of the paper capacitors of different types (temperature of 20-60°C): ● - metalized-paper single-layer; O - foil, saturated with ceresin; □ - foil, impregnated by octol; Δ - foil, saturated with oil.

Key: (1). Dose, rad (polyethylene).

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Dielectric constant this mixture can be determined according to formula (3.1), assuming/setting  $k \rightarrow 0$ . After conversion we will obtain

$$\ln \epsilon_n = y \ln \epsilon_r + (1 - y) \ln \epsilon_{no}. \quad (3.6)$$

In formula (3.6)  $\epsilon_r$  and  $\epsilon_{no}$  - dielectric constants of gas and strictly saturating mass;  $y$  - relative volumetric content of gas in saturating mass ( $y = v_r/v_n$ ).

If one considers that the dielectric constant any gas is close to one, then expression (3.6) will be simplified

$$\epsilon_n = \epsilon_{no}^{(1-y)}. \quad (3.7)$$

Utilizing formula (3.2), it is possible to determine a relative change in the dielectric constant paper  $\epsilon/\epsilon_0$ . After substituting this value into formula (3.5) taking into account expression (3.7), let us determine a relative change in the capacitance

$$\frac{\Delta C}{C_0} = - \left[ 1 - \frac{\frac{1-x}{x\epsilon_{no}} + \epsilon_{no}^{-1}}{\frac{1-x}{x\epsilon_n} + \epsilon_{no}^{-(1-y)}} \right]. \quad (3.8)$$

Since gas density is several orders less than the density of the saturating mass, then it is possible to consider with a sufficient precision/accuracy that the weight and the space of the substance of saturation remain constants. Then

$$y \approx \frac{v_r}{v_{no} + v_r} \text{ and } (1-y) = \frac{1}{1 + v_r/v_{no}}, \quad (3.9)$$

where  $v_{no}$  - initial space of the saturating mass.

Now it is possible to rate/estimate a maximally possible change

of the capacitance as a result of the formation of gas bubbles in the saturating mass within the section of capacitor, by assuming that in the process of saturation all pores of paper are filled with the saturating mass ( $\epsilon_k$  we consider it thus far constant/invariable):

$$\left(\frac{\Delta C}{C_0}\right)_{\max} = \lim_{v_1 \rightarrow \infty} \left(\frac{\Delta C}{C_0}\right) = -\frac{1 - \epsilon_{110}^{-1}}{1 + \frac{1-x}{x\epsilon_{k0}}}.$$

In all series radio-capacitors/radio-condensers is utilized the paper, whose density  $\rho = 1.25 \text{ g/cm}^3$ . If we accept the density of cellulose  $\rho_k = 1.55 \text{ g/cm}^3$  [26], then  $x = 1 - \rho/\rho_k = 0.2$ . The value of the dielectric constant of the majority of the utilized saturating masses lies/rests within limits of 2.1-2.5. Let us assume  $\epsilon_{110} = 2.2$  and  $\epsilon_{k0} = 6.6$ . Then  $(\Delta C/C_0)_{\max} = -34\%$ . The obtained change in the capacitance corresponds to the complete replacement of the saturating mass within the section by gas. Virtually this value must be equal to an increment in the capacitance of capacitor after saturation.

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Thus, the decrease of capacitance only as a result of a change in the properties of saturation can comprise to 25-40% (here it is considered, in contrast to the calculated evaluation/estimate, possible spread of value  $x = 0.2-0.35$ ; the effect of the regions, determined by the loose fit of foil to the paper; imperfect

saturation and other factors).

The numerals examined are maximum. They can be achieved/reached only during the specific construction/design of capacitor and it is sufficient high radiation dose rate. Actually/really, it is necessary for the formation of bubbles of gas in the saturation that the accumulation of the molecules of gas, which were being formed as a result of interaction of radiation/emission with the substance, would occur in the saturating mass. But this process is accompanied also by the diffusion of the molecules of gas from the section of capacitor into the external space. At the very low radiation dose rate the majority of the forming molecules of gas will succeed in emerging through the ends/faces of sections and their steady concentration within the section will be small. At the high dose rate it is possible to disregard diffusion; therefore all formed molecules participate in the formation of bubbles of gas and the effect in question is maximum.

The magnitude of effect depends also on the construction/design of capacitor. All preceding/previous reasonings concerned events in the open construction/design, i.e., was examined the case, when section is communicated with the atmosphere (housing is nonhermetic) or when space between the housing and the section is filled with gas and it is sufficiently great. However, in practice the

constructions/designs of capacitors with sealed housing and a comparatively small volume of gas within the housing (let us name/call this construction/design of "filled") are encountered. The possibilities of the frothing of saturation are sharply limited in this case, since the rapidly growing pressure within the housing resists an increase in the space of saturation. Consequently, the relative content of gas pockets in the saturating mass will be considerably less than in the open construction/design.

These representations make it possible to produce the calculation of a change of the capacitance of the saturated capacitor under varied conditions for irradiation. At a small radiation dose rate, when the dominant role play the processes of the diffusion of gas molecules, the solution of this problem is hindered/hampered. However, the calculation considerably is simplified in the case of the high radiation dose rate, since it is possible to disregard diffusion.

Let us assume that the saturating mass is perfectly plastic substance, i.e., to certain limiting value of the acting force  $f$  this solid inelastic body, and after this limit - ideal (absolutely incompressible and absolutely inviscid) liquid. If gas bubble was formed in this substance, then pressure in it will be always constant and will exceed external pressure  $p_0$  on value  $f$  ( $p = p_0 + f$ ).

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In this case the equation of state of gas within the bubbles can be represented in the form

$$v_r(p_g + p) = q_r \frac{RT}{M}, \quad (3.10)$$

where  $q_r$  - mass of gas in the bubbles;  $M$  - molecular weight of gas;  $R$  - universal gas constant;  $T$  - absolute temperature.

If the power of the absorbed radiation dosage in the substance of saturation is equal to  $P$  [rad/s] and the radiation chemistry yield of gas (quantity of molecules of gas on 100 eV of absorbed energy) is equal to  $G$ , then, taking into account that 1 rad=100 erg on 1 g of substance, it is possible to determine a quantity of molecules of gas, which are formed per unit time per unit of volume of the saturation

$$n_g \approx 6,25 \cdot 10^{14} G \rho_{\text{sat}} P, \quad (3.11)$$

where  $\rho_{\text{sat}}$  - density of the saturating mass.

It is possible to assume that the formation of bubbles is started not immediately after the beginning of irradiation, but only after certain time  $t_0$ , during which molecule concentration of the

isolated gas will achieve this value, with which the gas pressure in the formed bubble will exceed external pressure on value  $f$ . Then the quantity of gas, which went to the formation of bubbles, is equal

$$q_r = n_0(l - l_0) v_{n0} \frac{M}{N_A}, \quad (3.12)$$

where  $N_A$  - Avogadro number.

Let us examine the filled construction/design of capacitor. The equation of state of gas in the space between the section and the housing can be recorded in the following form:

$$p_n(V_r - v_r) = Q_r \frac{RT}{M}, \quad (3.13)$$

where  $V_r$  and  $Q_r$  - space and the mass of the gas between the section and the housing before the irradiation.

Since in the case in question entire isolated gas remains within the section, then the weight of gas  $Q_r$  does not change in the process of irradiation and it is possible to determine equations, analogous (3.13):

$$Q_r = V_r p_0 \frac{M}{RT}, \quad (3.14)$$

where  $p_0$  - initial pressure between the housing and the section.

Substituting the value  $Q_r$  from formula (3.14) in (3.13), let us find

$$p_n = p_0 \frac{V_r}{V_r - v_r}. \quad (3.15)$$

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Solving equation (3.10) taking into account formulas (3.12) and (3.15), let us determine the value of relation  $v_r/v_{no}$  and after substitution in (3.9) we obtain value  $(1-y)$ .

The specified conditions for irradiation and constructing/designing the capacitors are examined in the practical calculations; therefore let us pause at some special cases.

When the viscosity/ductility/toughness of the saturating mass is small (in the capacitors with the liquid saturations, also, at sufficiently high temperatures), value  $f$  much less  $\rho_n$  (at least, after certain exposure time). Then

$$1 - y = \frac{1 + B(D - D_0) \frac{1}{V_r/v_{no}}}{1 + B(D - D_0) \frac{1}{V_r/v_{no}} (1 + V_r/v_{no})}, \quad (3.16)$$

where  $D = Pt$ ;  $D_0 = Pt_0$ ;  $B = 6,25 \cdot 10^{11} G \rho_{no} \frac{RT}{\rho_0 N}$ .

Assuming/setting for evaluation/estimate  $G=3$ ,  $\rho_{no}=1$ ,  $T=300$  K, value  $B$  we will obtain order  $10^{-7}$  rad.

With the high viscosity of the saturating mass in certain range of exposure time condition  $f \gg \rho_n$  can be satisfied. In this case

$$(1-y) = \frac{1}{1 + \frac{B\rho_0}{f} (D - D_0)} \quad (3.17)$$

In the open construction/design of capacitor at any value of  $f$  external pressure  $p_u = 1$  atm. and

$$(1-y) = \frac{1}{1 + \frac{B}{1+f} (D - D_0)} \quad (3.18)$$

The change in the capacitance of capacitor, caused by the frothing of saturation, can be calculated according to formula (3.8), substituting in it value  $(1-y)$  from formulas (3.16), (3.17) or (3.18).

It follows from the given dependences that the capacitance of capacitor will decrease with an increase in the absorbed radiation dosage in all cases, reaching comparatively rapidly value minimum for this version of construction/design.

In the case of the filled construction/design and liquid saturation the minimum value of a change of the capacitance is determined by value  $(1-y)$  from formula (3.16) with  $D \rightarrow \infty$ , i.e., by value

$$1-y = \frac{1}{1 + V_r/v_{no}} \quad (3.19)$$

Consequently, a maximum change in the capacitance depends on the ratio of the volume of gas within the housing to the space of saturating mass ( $V_r/v_{uo}$ ).

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In the extreme case of the complete filling of housing with saturation the space of gas within the housing vanishes (virtually sufficient to satisfy the condition  $V_r/v_{uo} \ll 1$ ) and value  $(1-y)$  equal to one. In this case  $(\Delta C/C_0) = 0$ .

If housing is nonhermetic, then  $V_r \rightarrow \infty$  and  $(1-y) \rightarrow 0$ , which corresponds to the already examined maximum change in the capacitance when  $v_r \rightarrow \infty$ :  $\Delta C/C_0 = -(25-40)\%$ . Thus, only due to variations in the construction/design of capacitor it is possible to observe the fluctuations of the maximum decrease of capacitance almost in entire range of possible changes.

The measurement of the unimpregnated samples/specimens of paper capacitors showed a change in the dielectric constant cellulose

$$\epsilon_k = \epsilon_{k0} + 10^{-4} D^{0.73} \quad (3.20)$$

$$(\epsilon_{k0} = 6.6).$$

This relationship/ratio (3.20) is checked for the absorbed radiation dosages to  $5 \cdot 10^4$  rad. Substituting the value  $\epsilon_{\text{H}}$  from (3.20) in (3.8), it is possible to rate/estimate a relative change of the capacitance of paper capacitor as a result of changing the properties of cellulose.

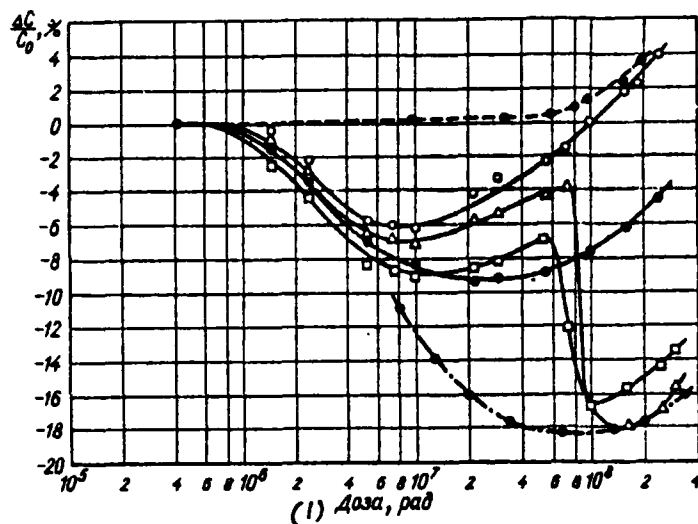


Fig. 3.3. Change in the capacitance of one type paper foil capacitors.

Key: (1). Dose, rad.

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Fig. 3.3 gives the typical dependences of a change in the capacitance of small/miniature paper foil capacitor with the cylindrical housing, filled with the liquid saturation (octol) on the radiation dosage. The sharp decrease of capacitance, observed in two samples/specimens, is connected with the depressurization of housing. Lowest graph/curve corresponds to the capacitors, whose housing before the experiment was specially unsealed. Upper graph/curve is obtained on gamma-ray source ( $\text{Co}^{60}$ ) at the low dose rate. Remaining

results are the consequence of the radiation effect of the reactor of large rate of the dose (temperature in this case did not rise above 60°C). These experimental data satisfactorily confirm calculated dependences.

A change in the capacitance of paper capacitors depends also on the viscosity/ductility/toughness of saturation. The formation of bubbles hinders with an increase in the viscosity/ductility/toughness. Formulas (3.17), (3.18) show that in the extreme case, when  $f \rightarrow \infty$  (the jelly impregnation), change in the space of saturation will not occur. Then determining must be a change in the dielectric constant cellulose and, therefore, capacitance of capacitor must increase. A change in the capacitance of the single-layer metalized-paper capacitors of small amount of capacitance, saturated with ceresin (see Fig. 3.2) is a characteristic example of this case.

The strain of sections (as a result of the barrel-shaped strain of housing) can exert in comparatively large-size capacitors, which have rectangular housing, noticeable effect on a change in the capacitance. The airtightness of housing as long as is retained, this process is developed in the slower (depending on radiation dosage) decrease of capacitance of capacitor. A maximum change in the capacitance frequently is more than in the "open" construction/design

of the same capacitor.

Unfortunately, the phenomena examined to a considerable extent depend on the physicomachanical properties of materials and in view of the variety of the occurring processes cannot be designed accurately.

It must be noted here that the processes, which occur in the saturation (, first of all, in the liquid and the Vaseline-like), important not only in the paper capacitors, but also in other types of the saturated capacitors (combined, tape/film, etc.).

The tests conducted show that paper capacitors to undesirably utilize in the doses, which exceed approximately/exemplarily  $10^4$  rad ( $10^{15}$  neutrons/cm<sup>2</sup>,  $E > 2.9$  MeV). This is clearly evident from the results of the statistical tests of one type paper capacitors, given in Fig. 3.4 [10].

Film capacitors. The results of experiments show that a change in the capacitance of capacitors of this type does not exceed  $\pm 15\%$  to absorbed doses on the order of  $10^4$  rad and neutron fluxes  $10^{17}$  neutrons/cm<sup>2</sup> ( $E > 2.9$  MeV).

At doses to  $10^4$  rad and temperature of 20-40°C in Soviet

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capacitors changes of the capacitance within the limits of portion and units of percentages were observed. Capacitance of polystyrene and teflon capacitors in essence decreased (Fig. 3.5), and it increased in Dacron ones and triacetate ones.

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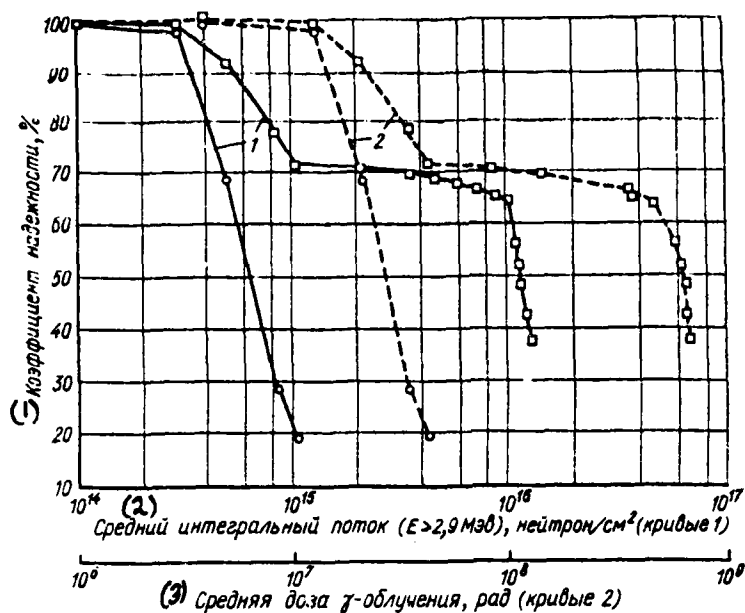


Fig. 3.4. Indices of reliability of paper capacitors (on the basis of tests of 100 samples/specimens); O - evaluation/estimate according to permissible change in capacitance (20%);  $\square$  - evaluation/estimate according to catastrophic breakdown.

Key: (1). Coefficient of reliability, %. (2). Average/mean integrated flux ( $E > 2.9$  MeV), neutrons/cm<sup>2</sup> (curves 1). (3). Average dose of gamma-irradiation, rad (curves 2).

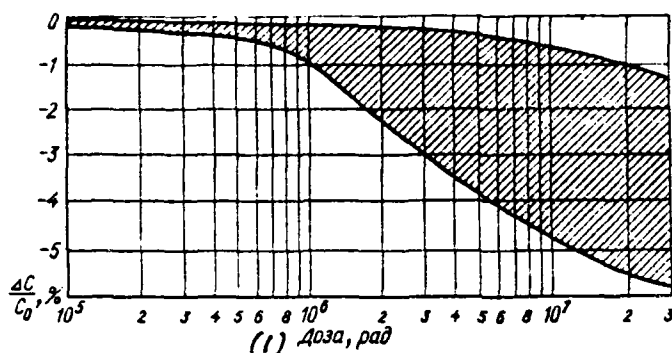


Fig. 3.5. Change in capacitance of teflon capacitors.

Key: (1). Dose, rad.

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Nature of the observing changes in the capacitance of these capacitors is not in detail investigated. In a number of cases, possibly, occur the chemical processes in the materials, caused or accelerated by irradiation, for example further polymerization, oxidation processes, change in the structure of fundamental molecular chains. The damage of supermolecular structure can affect also, since it is known [8] that the disordered state of polymeric materials increases with an increase in the absorbed energy of radiation/emission, decreases the degree of crystallinity and, therefore, substance density decreases. In the polymeric materials of the type of Lavsan, which have the high degree of crystallinity under

the normal conditions, this can lead to an increase in the capacitance due to an increase in the relaxation polarization upon transfer of crystalline phase into the amorphous.

certain representation about the statistics of breakdown of Dacron capacitors gives Fig. 3.6 [10]. These results are obtained during the testing in nuclear reactor, i.e., under the simultaneous influence of neutrons and  $\gamma$ -quanta. Irradiation only by  $\gamma$ -quanta must lead to the same changes in the identical dose in rad (taking into account the contribution of neutrons in the case of reactor radiation/emission), since a change in the properties of polymeric materials is determined in essence by the absorbed dose, but not by the form of radiation/emission.

A change in all properties of these substances is the characteristic feature of the effect of neutron and  $\gamma$ -radiations on the organic materials, the irreversible changes in the electrical parameters considerably less depending on radiation dosage than, let us say, the mechanical characteristics (Table 3.2) [39].

Table 3.2. Comparative data about the effect of irradiation on the electrical and mechanical properties of some organic dielectrics.

(1) Материал	(2) Допустимая температура, °C	(3) Максимально допустимая доза облучения, Mrad	
		(4) по электрическим свойствам	(5) по механическим свойствам
(6) Фторопласт-4	250	2500	2,5
(7) Лавсан	100	500	250
(8) Полиэтилен	85	5000	250
(9) Полистирол	75	5000	500

Key: (1). Material. (2). Permissible temperature, °C. (3). Maximum permissible radiation dose, Mrad. (4). according to electrical properties. (5). according to mechanical properties. (6). Teflon. (7). Lavsan. (8). Polyethylene. (9). Polystyrene.

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This position makes it necessary very carefully to approach the evaluation/estimate of the criterion of efficiency and thereby to the problem of the reliability of the work of capacitors with the organic dielectric under radiation conditions. In a number of cases it is possible to commit serious error during the determination of the radiation stability of capacitors, if we proceed from the usual methods of the evaluation/estimate of efficiency. Teflon capacitors are exponential in this respect. As seen from Fig. 3.5, change in the capacitance of capacitors of this type it is small even in doses on

the order of 30 Mrad; the loss tangent and insulation resistance can remain also within the permissible limits. Such experimental results, it would seem, give grounds to utilize capacitors in the equipment even in the such large radiation dosages.

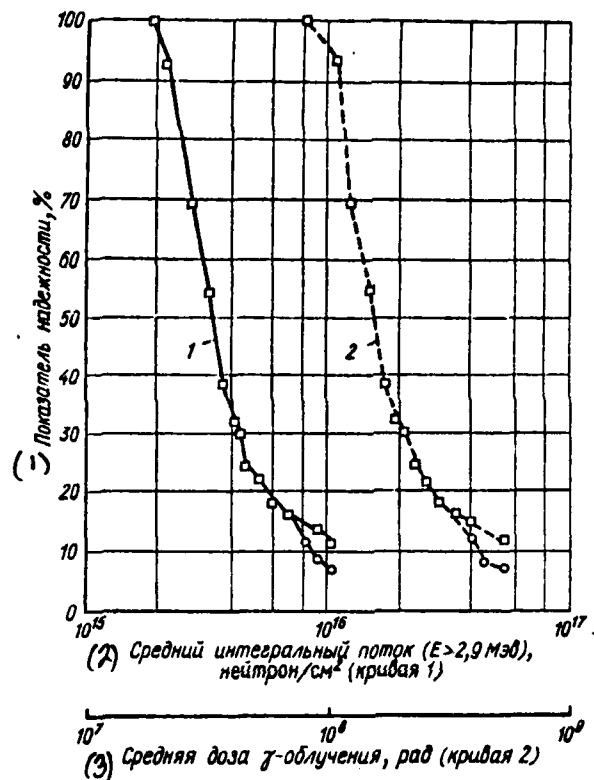


Fig. 3.6. The indices of the reliability of Dacron capacitors (on the basis of tests of 98 samples/specimens): O - evaluation/estimate according to the permissible change in capacitance (10%);  $\square$  - evaluation/estimate according to catastrophic breakdown.

Key: (1). Index of reliability, %. (2). Average/mean integrated flux ( $E > 2.9$  MeV), neutrons/cm<sup>2</sup> (curve 1). (3). Average dose of gamma-irradiation, rad (curve 2).

It is at the same time known (see Table 3.1), that the mechanical properties of teflon change catastrophic in the considerably smaller absorbed doses. Consequently, efficiency of teflon capacitors actually/really can be preserved to comparatively large radiation dosages, thus far are absent mechanical loads on teflon. However, the reliability of the work of capacitors in these conditions sharply descends, since the appearance of mechanical loads can cause rapid breakdown of capacitor.

This example shows that for the selection of the criterion of evaluation of efficiency and further study of the reliability of the work of capacitors with the organic dielectric it is necessary to combine the measurements of electrical characteristics with the mechanical tests.

Consequently, at present during the selection of film capacitors for the work in the fields of the ionizing radiations/emissions it is necessary to consider a change of the structural and, correspondingly, mechanical properties of polymer films, comparing them with the character of a change in the electrical parameters.

Capacitors with the inorganic dielectric. These capacitors have

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the greatest radiation stability. Usually a change in their capacitance does not exceed portions or units of percentages at a neutron flux to  $10^{14}$  neutrons/cm<sup>2</sup> ( $E > 2.9$  MeV) and a temperature of 30-50°C.

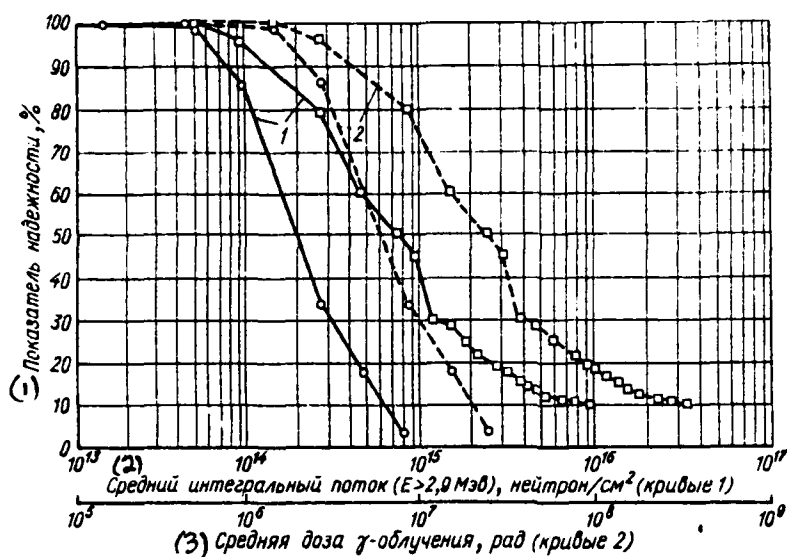


Fig. 3.7. The indices of the reliability of solid tantalum capacitors (on the basis of testing 98 samples/specimens):  $\square$  - evaluation/estimate according to the permissible change in capacitance (20%);  $\circ$  - evaluation/estimate according to the permissible change in the coefficient of scattering (6%).

Key: (1). Index of reliability, %. (2). Average/mean integrated flux ( $E > 2.9$  MeV), neutrons/cm<sup>2</sup> (curves 1). (3). Average dose of gamma-irradiation, rad (curves 2).

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Exception are the low-frequency ceramic capacitors, a change of capacitance of which in these conditions for the separate

samples/specimens reaches 10-25%.

Oxide capacitors. Change in the capacitance of aluminum dry electrolytic capacitors does not give any well reproducible laws from the radiation dosage. During comparatively short-term tests (tens of hours) the relative change in the capacitance was within the limits  $\pm(10-20)\%$  to the doses of the order of several ten megarads and fast neutron flux  $10^{13}-10^{14}$  neutrons/cm<sup>2</sup>. Some samples/specimens of capacitors in this case were unsealed as a result of the radiolysis of electrolyte.

During irradiation in the reactor a change in the capacitance of liquid tantalum capacitors also had irregular character in the limits  $\pm 5-10\%$  to doses on the order of 10 Mrad and fast neutron flux  $10^{13}$  neutrons/cm<sup>2</sup>. However, similar results were observed during testing of oxide-semiconductor capacitors. The data of the statistical experimental studies of a change in capacitance and loss tangent of one of solid tantalum capacitors are cited in Fig. 3.7 [10]. Irradiation was conducted in the reactor at a temperature of 85°C.

The results of other tests of tantalum and niobium capacitors make it possible to consider that these capacitors are virtually operational to the neutron flux of approximately/exemplarily  $10^{14}$  neutrons/cm<sup>2</sup> ( $E > 2.9$  MeV). It was noticed that a decrease in the

operating voltage/stress increases the service life of capacitors under these conditions.

### 3.3. Change in the loss tangent.

From the general theory of dielectric losses it is known [28] that the losses in the dielectrics of capacitor are composed of the losses of through conductivity and losses, connected with different forms of the slowly established/installed polarization. The conductivity of electrical insulating materials is insignificant under the normal conditions at not too high temperatures. Therefore its effect on the losses is developed only at the very low frequencies. With an increase in the frequency the polarizational losses, which considerably exceed the losses of through conductivity, acquire primary meaning.

The conductivity of all dielectrics strongly grows/rises in the process of irradiation. This leads to an increase in the losses especially at the low frequencies (Fig. 3.8) [40]. In a number of cases polarizational losses become unessential in comparison with the losses of conductivity. Then  $\operatorname{tg} \delta = \sigma_p / \omega \epsilon \epsilon_0$ . During irradiation of air capacitors this form of losses is basic.

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The losses of conductivity are connected, mainly, with the ionizing processes of interaction of radiation/emission with the substance. The more complicated dependences of a change in the loss tangent on the radiation dose rate, temperature and frequency were observed in some organic materials. In particular, the effect of the degree of the crystallinity of polymeric material on a change in the loss tangent during irradiation (Fig. 3.9) [9] was noticed. Measurement in one experiment of ohmic conductivity and losses showed that the irradiation affects not only the processes of electrical conductivity, but also polarization. Moreover this effect is greater, the higher the degree of the crystallinity of sample/specimen. Table 3.3 gives the results of the comparison of the measured ohmic conductivity and the conductances, calculated according to the formula  $\sigma = \omega \epsilon \operatorname{tg} \delta$ .

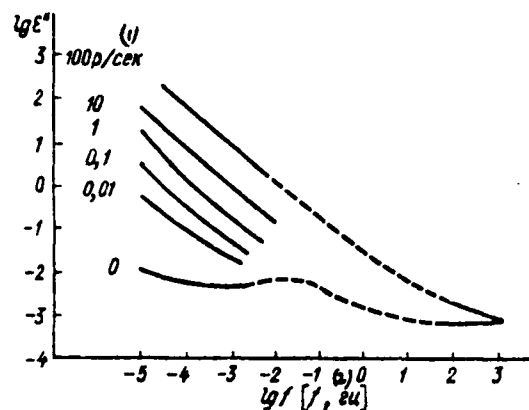


Fig. 3.8. Dependence of the factor of loss of teflon on the frequency at the different radiation dose rate.

Key: (1). r/s. (2). Hz.

Table 3.3. Calculated ( $\sigma_{\text{расч}}$ ) and measured ( $\sigma_{\text{изм}}$ ) values of the ohmic conductivity of Lavsan ( $\times 10^{-11} \Omega^{-1} \text{ cm}^{-1}$ ) of the different degree of crystallinity (temperature of 20°C).

(1) Степень кристаллическости, %	(2) Проводимость				$\sigma_{\text{расч}} - \sigma_{\text{изм}}$	
	(3) до облучения		(4) при облучении		(5) до облучения	(6) при облучении
	(7) расчетная	(8) измеренная	(9) расчетная	(10) измеренная		
0	1,97	0,003	2,09	0,06	1,97	2,04
65	0,21	0,161	1,97	0,55	0,05	1,42

Key: (1). Degree of crystallinity, %. (2). Conductivity. (3). before irradiation. (4). during irradiation. (5). calculated. (6). measured.

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The difference between the calculated and measured values characterizes the conductivity, connected with the polarization of sample/specimen.

In certain cases a change of the losses is not connected with a change in the electrical conductivity. With an increase in the conductivity of sample/specimen during the irradiation the loss tangent can even be reduced in the specific frequency band [41]. The latter is connected with the observing shift/shear of the maximum of the frequency dependence  $\tan \delta$  the polar dielectrics to the side of lower frequencies.

In all types of capacitors the loss tangent increases during the irradiation and depends on the radiation dose rate. A relative change in the losses usually lies/rests in the range from several ten to several hundred percent.

Residual/remanent changes are most great in paper capacitors. In the absorbed doses of  $10^4$ - $10^5$  rad the loss tangent of these capacitors can increase several times, and in a number of cases 10-20 times.

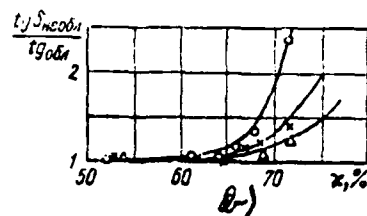
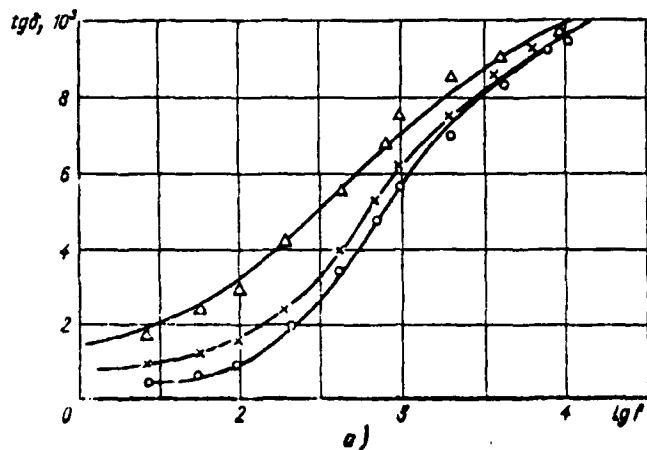


Fig. 3.9. A change in the loss tangent of the polymers of the different degree of crystallinity  $\kappa$  during the gamma-irradiation: a) Lavsan: O - before the irradiation; X - during irradiation ( $\kappa=0\%$ );  $\Delta$  - during irradiation ( $\kappa=65\%$ ); b) polyethylene: O - 100 Hz; X - 1 kHz;  $\Delta$ -10 kHz.

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### 3.4. Change in the insulation resistance.

From the dielectric parameters of capacitors the insulation resistance is most sensitive to the irradiation. The observing changes have the reversible character in essence and are caused by an increase in the conductivity of electrical insulating materials and air surrounding sample/specimen.

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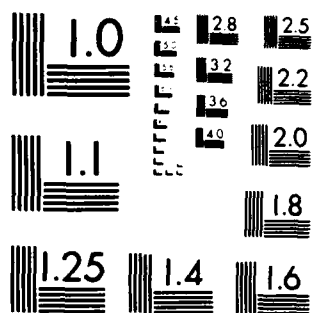
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In general form the insulation resistance depends on capacitance value, type of capacitor, construction/design and conditions for use/application. However, if we eliminate the effect of the conductivity of air (for example, with the aid of the filling of samples/specimens by plastic) and to examine capacitors of sufficiently great capacity, then insulation resistance will be determined only by bulk properties of fundamental dielectrics. Then any capacitor independent of type and construction/design can be characterized with the value of its own time constant

$$\tau = RC = \frac{\epsilon_0}{\sigma} s,$$

where R - insulation resistance, ohms; C - capacitance, F;  $\sigma$  - specific conductivity  $(\Omega \cdot \text{cm})^{-1}$ ;  $\epsilon$  - relative dielectric constant;  $\epsilon_0 = 8.85 \cdot 10^{-14}$  F/cm.

Under the normal conditions (before irradiation) the time constant depends on the quality of utilized materials and technology of the production of capacitor. This value can have a scatter in the sufficiently large limits even in one type capacitors (Table 3.4) [26].

Table 3.4. Time constant of the capacitors of different types.

(1) Конденсатор	(2) $\tau_0$ при 20° С, 10 <sup>3</sup> сек		(3) Мощность дозы <sup>1</sup> при $\tau_0 = \tau_p$ р/сек
	(4) Норма	(5) Верхний предел	
Полистироловый (6)	5	1000	1
Фторопластовый (7)	5	1000	0,1
Лавсановый (8)	4	1000	46
Металлобумажный (однослойный) (9)	0,2	0,5—1	10
Танталовый электролитический жидкостный (10)	0,3—0,5	2—3	400
Алюминиевый электролитический сухой (11)	0,02	0,1—0,3	10

Key: (1). Capacitor. (2). with 20°C, 10<sup>3</sup> s. (3). Rate of dose <sup>1</sup> when r/s.

FOOTNOTE <sup>1</sup>. Calculated evaluation/estimate, on the basis of the norm on 10. ENDFOOTNOTE.

(4). Norm. (5). Upper limit. (6). Polystyrene. (7). Teflon. (8). Dacron. (9). Metalized-paper (single-layer). (10). Tantalum electrolytic liquid. (11). Aluminum electrolytic dry.

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Under radiation conditions a change in the capacitance of capacitors does not exceed 20-30%. The value of time constant, as under the normal conditions, it is determined in essence by a change in the insulation resistance. Therefore it is possible to accept in the calculations with a precision/accuracy sufficient for the

practice that the capacitance of capacitor remains constant ( $C_p \dot{=} C_0 = C$ ). Then the equivalent schematic of capacitor with irradiations will be the same as under the normal conditions (in the form of parallel connection of capacitance and insulation resistance), but with supplementary back-out resistor of  $R_{in}$ . In this case

$$\frac{1}{\tau} = \frac{1}{\tau_0} + \frac{1}{\tau_p},$$

where  $\tau_0 = R_0 C$  — time constant to the irradiation;  $\tau_p = R_{in} C$  — time constant during the irradiation.

A change in the time constant of capacitor during the irradiation can depend on initial time constant (especially at a small dose rate). The worse the quality of dielectric (the less  $\tau_0$ ), the greater must be the rate of the dose, in which begins the change  $\tau$  (Table 3.4). And vice versa, the better the insulating properties of material, the greater the relative changes in the insulation resistance at the prescribed/assigned radiation dose rate and, consequently, also the more considerable the change in the time constant.

At the large power of dose  $\tau_p \ll \tau_0$  and

$$\tau = \tau_p = R_{in} C = \frac{\epsilon_0 \epsilon}{\sigma_p} \text{ s}, \quad (3.21).$$

Stray current, which corresponds to this its own time constant,

is equal to

$$I_p = \frac{U}{R_w} = UC \frac{\sigma_p}{\epsilon_0 \epsilon} a, \quad (3.22)$$

where U - voltage across capacitor, V.

Formulas (3.21) (3.22) make it possible to determine insulation resistance and stray current, if specific dielectric conductance under the given conditions for irradiation and dielectric constant of material is known. However, in many instances it is systematic difficult to measure the induced conductivity in the samples/specimens of material. Then measurements are carried out in the samples/specimens of capacitors and, using formula (3.22), they calculate  $\sigma_p^* = \sigma_p/\epsilon$ . In this case it is not always possible to determine dielectric constant with a sufficient precision/accuracy. In this case to more conveniently use directly measured value  $\sigma_p^* [s^{-1}]$ . In accordance with formulas (3.21) (3.22)

$$\tau_p = \frac{1}{\sigma_p^*}, \quad I_p = UC\sigma_p^*, \quad (3.23)$$

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By analogy with the electrical conductivity of dielectrics  $\sigma_p^*$  it is possible to represent in the form

$$\sigma_p^* = BP^A, \quad (3.24)$$

where  $B=A/\epsilon_0 \epsilon (p^A \cdot s^{1-A})^{-1}$ ; P - dose rate, R/s.

The effect of air surrounding sample/specimen will be developed in the form of the supplementary shunting conductivity. Under the conditions for irradiation air - the worst insulator and in a number of cases of leak/leakage by air they can several times, and several orders exceed leaks/leakages on the solid dielectrics of capacitor. The current strength in this case is determined not only by the layout of the external electrodes of capacitor, but also surrounding sample/specimen structural elements/cells, especially metallic. Therefore conductivity by air in the majority of the cases is not the characteristic of capacitor as radio parts, but are determined procedure of measurements or construction/design of radio-electronic unit with the capacitor.

With small nominal capacitance of capacitor calculation according to the given formulas gives the high result for the radiation time constant, since the shunting conductivity of the auxiliary dielectrics of capacitor is not considered in them. To consider this effect in general form is virtually impossible; therefore it is necessary to use only the results of the experimental studies of each specific sample/specimen of capacitor.

In order to rate/estimate the degree of the effect of current

leaks using the auxiliary materials either creepages, samples/specimens with different ratio of the volume of materials to the surface usually are measured, through which are possible supplementary current leaks, or with different relationship/ratio of fundamental and auxiliary materials. If relative changes in the parameter remain constants for all samples/specimens, then it is considered that the characteristics of material are determining. During the tests of series radio parts such investigations are hindered/hampered, since it is not always possible to fit the necessary set/dialing of samples/specimens from those, which release industry.

The results of measuring of the stray current of one type capacitors under the identical conditions for irradiation make it possible to consider that with the capacitance more than several thousand picofarads is the determining factor the volumetric radiation conductivity of the fundamental dielectrics of capacitor (if we eliminate the effect of air). This is confirmed by the dependence of a relative change in voltage across capacitor (value, proportional to conductivity) from the capacitance, given in Fig. 3.10.

During the use in the capacitor of a heterogeneous dielectric (saturated paper, paper lavsan, etc.) the character of a change in the stray current during irradiation can essentially change, especially in the nonstationary system. For some simplest heterogeneities (for example, if we admissibly consider dielectric as two-layered) it is possible to utilize known dependences of the conductivity of such materials on the characteristics of separate layers [28].

The insulation resistance in the majority of the cases is reduced after the cessation/discontinuation of irradiation. Recovery time depends on the form of dielectric, temperature, dose and radiation dose rate. Capacitors with the inorganic dielectric most rapidly reduce their characteristics. According to the data of A. P. Novoselov in the ceramic, glass-enamel and mica capacitors two hours after irradiation to the doses of  $10^4$ - $10^5$  rad ( $\gamma$ -radiation Co<sup>60</sup>) the insulation resistance in practice did not differ from initial (to the irradiation) value. Also were not observed changes in metalized-paper capacitors after the doses of  $10^4$ - $10^5$  rad. However, after the doses of  $10^5$  rad was noted the decrease of the insulation resistance of these capacitors on partial order. The foil paper capacitors two hours after irradiation had in a number of cases insulation resistance considerably lower than the established/installed norm and only for 240-264 h all investigated samples/specimens reduced their

parameters to the permissible limits (Table 3.5). Analogous changes in the insulation resistance were observed in the polystyrene and fluoroplastic capacitors. The character of the restoration/reduction of the insulation resistance of these capacitors is given in Fig. 3.11.

Despite the fact that the mechanical properties of polytetrafluoroethylene strongly change in the doses less than  $10^7$ - $10^8$  rad, teflon capacitors went out of order only after the dose of approximately/exemplarily  $10^8$  rad (insulation resistance decreased by seven orders and subsequently was not reduced).

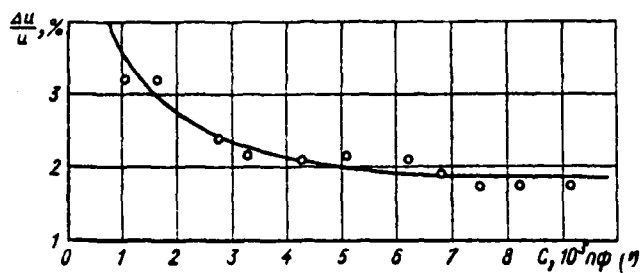


Fig. 3.10. Relative change in the voltage on the mica capacitors with the different value of capacitance.

Key: (1). pF.

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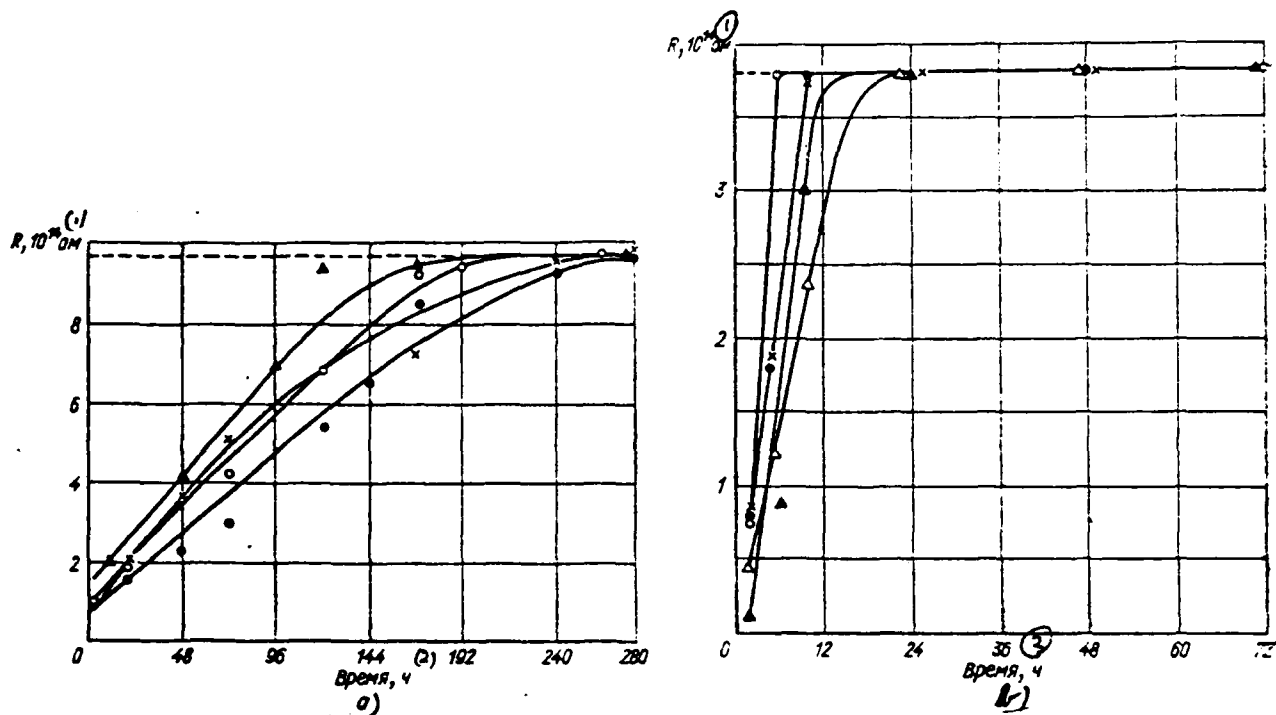


Fig. 3.11. Restoration/reduction of insulation resistance of capacitors after effect on them of  $\gamma$ -radiation  $\text{Co}^{60}$ : a) polystyrene:  $\Delta$  -  $10^4$  R with 1100 R/s; X -  $10^7$  R with 1100 R/s; O -  $10^8$  R with 1100 R/s;  $\bullet$  -  $10^9$  R with 425 R/s; b) fluoroplastic: O -  $10^4$  R with 10 R/s; X -  $10^4$  R with 100 R/s;  $\bullet$  -  $10^4$  R with 1100 R/s;  $\Delta$  -  $10^7$  R with 100 R/s;  $\Delta$  -  $10^7$  R with 1100 R/s.

Key: (1). Ohms. (2). Time, h.

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This again shows that the electrical characteristics of organic materials are less sensitive to the disturbances/breakdowns in the structure of material in comparison with the mechanical characteristics.

The stray current of aluminum and liquid tantalum chemical capacitors in a number of cases changes insignificantly (1.0 - 3.6). At the same time is observed the case of an abrupt change in the current, and also the total loss of efficiency of aluminum capacitors as a result of the depressurization of samples/specimens, caused by the radiolysis of electrolyte.

Changes in the characteristics of these capacitors are connected, probably, with a change in the physicochemical properties of materials. Electrical characteristics are the consequence of these processes and do not have therefore good reproducibility.

### 3.5. Change in dielectric strength.

Dielectric strength of dielectric they characterize with the value of the intensity/strength of field  $E_{\text{lim}}$  with which begins the

breakdown. They usually consider that in the majority of capacitors the electric field in the fundamental interelectrode gap/interval is close to the uniform, and therefore the appropriate voltage of the breakdown of capacitor can be represented in the form:  $U_{up} = E_{up}d$ , where  $d$  - thickness of dielectric.

In the gaseous dielectrics in the first approximation, the breakdown is determined by the condition, under which the multiplication of electrons in the electric field becomes infinite and current strength is limited only to the parameters of external circuit.

Table 3.5. Insulation resistance of foil paper capacitors after the effect on them of  $\gamma$ -radiation Co<sup>60</sup>.

(1) Режим облучения		(2) Сопротивление изоляции, $10^{10}$ ом				
(4) доза, p	(5) мощность дозы, p сек	(6) до облучения	(3) после облучения через			
			(7) 2 ч	264 ч	1800 ч	3120 ч
10 <sup>6</sup>	10	8,58	2,68	4,92	7,12	4,74
	100	10,54	1,82	—	6,82	5,66
	1100	10,40	2,32	6,26	9,10	9,36
10 <sup>7</sup>	100	4,80	0,83	2,27	1,74	2,32
	1100	13,70	0,87	—	1,34	4,26
10 <sup>8</sup>	1100	12,72	0,99	1,50	1,28	2,00
10 <sup>9</sup>	425	10,56	0,08	1,64	2,28	1,28

Key: (1). Mode/conditions of irradiation. (2). Insulation resistance,  $10^{10}$  ohms. (3). after irradiation through. (4). dose. (5). rate of dose, r/s. (6). before irradiation. (7). h.

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The value of initial ionization by external radiation source, apparently, is not determining for the creation of the conditions of breakdown and does not affect in limits of 10-20% the voltage/stress of breakdown [42]. The effect of the ionizing radiation/emission affects in the fundamental reduction time of discharge build-up. The time of discharge build-up decreases with an increase in the radiation dose rate.

The experimental check of electrical air-gap strength with the uniform electric field under varied conditions for irradiation, and also measuring the conduction currents of air with the strength of field, close to  $E_{up}$ , they show that even at the high intensities of the radiation/emission considerable changes in dielectric strength are not observed.

The charge carriers created in the gas rapidly recombine after the cessation/discontinuation of irradiation. Residual/remanent radiation changes in practice does not occur in comparatively small radiation dosages; therefore after irradiation dielectric strength of gas does not differ from its values under the normal conditions (to the irradiation).

Table 3.6. The stray current of oxide capacitors before and after the effect on them of  $\gamma$ -radiation  $\text{CO}^{60}$ .

(1) Конденсатор	(2) Режим облучения		(3) Ток утечки, мкА		
	(4) доза, р	(5) мощность дозы, р/сек	(6) до облучения	(7) после облучения через	
				(8) 2 ч	(9) 240 ч
(9) Алюминиевый электроли- тический сухой	10 <sup>6</sup>	10	5,6	4,7	1,5—3,6
		100	6,2	15,3	2,0—8,7
		1100	3,3	9,8	2,4—11,4
	10 <sup>7</sup>	100	5,0	3,3	0,8—2,6
		1100	5,1	4,9	0,5—2,1
	10 <sup>8</sup>	1100	3,7	3,8	0,6—3,9
	10 <sup>9</sup>	425	15,8	28,0	3,2—26,0
	(10) Танталовый жидкостный с объемно-пористым ано- дом	10 <sup>6</sup>	10	1,2	1,0
100			1,0	1,5	1,0—1,5
1100			1,1	1,5	1,0—1,5
10 <sup>7</sup>		100	1,0	1,3	1,1—1,6
		1100	1,0	1,6	1,1—1,3
10 <sup>8</sup>		1100	1,0	2,1	1,0—308
10 <sup>9</sup>		425	0,5	480	36—510

Key: (1). Capacitor. (2). Mode/conditions of irradiation. (3). Current of leak/leakage,  $\mu\text{A}$ . (4). dose. (5). rate of dose, r/s. (6). before irradiation. (7). after irradiation through. (8). h. (9). Aluminum electrolytic dry. (10). Tantalum liquid with bulk porous anode.

In the solids are distinguished three forms of the breakdown: electrical, thermal and electrochemical [43].

The first form of breakdown is determined just as in air, by sufficient for the ionization by energy of electrons, accumulated during their motion in the electric field, and by interaction of these electrons with the atoms of solid body. It is possible to assume that in the small doses (thus far did not occur noticeable structural changes), in the region of the electrical form of breakdown an increase of the initial concentration of charge carriers during the irradiation must not lead to considerable changes in dielectric strength, since the determining factor is energy of electron in the electric field, and not their concentration.

For some organic condenser/capacitor dielectrics this is confirmed by experiment. Measurements of dielectric strength (short-term breakdown) during and after irradiation in nuclear reactor in the identical doses did not give noticeable differences as obtained results.

In the region of the thermal form of breakdown important value acquires electrical conductivity of material. In the normal conditions the temperature is the fundamental reason for a change of dielectric conductance. Under the radiation effect supplementary

conductivity as a result of ionizing processes in the substance appears. This increase in the conductivity is equivalent to supplemental heat.

By thermal test/sample it is determined by the balance of heat in the dielectric and depends therefore on the construction/design of capacitor. In the contemporary capacitors the construction/design is designed so as not to allow/assume the thermal form of breakdown in the working temperature range. Consequently, if irradiation is conducted at low temperatures, then an increase in the conductivity to those limits, which are permitted at maximum operating temperatures, it is not dangerous from the point of view of thermal breakdown. A more considerable increase in the conductivity during irradiation, and also supplementary conductivity at maximum operating temperature can affect dielectric strength of capacitor. The degree of the effect of supplementary conductivity on dielectric strength depends on those real safety factors (on the conditions of thermal breakdown), which are laid in the construction/design of capacitor.

The most considerable change in the insulation resistance occurs during the pulse irradiation, since in this case the radiation dose rate can reach very high values. However, the duration of radiation effect does not usually exceed the units of milliseconds, but this time it is insufficient for the development of the thermal breakdown

of capacitor [26].

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The electrochemical form of breakdown is connected with the prolonged processes of the transfer of substance in the dielectric under the action of electric field. These processes proceed more effective during the irradiation. Experimental investigations in this region of breakdown were not conducted.

A change in dielectric strength of capacitors occurs also as a result of the damage of the structure of the materials, entering the construction/design of capacitor.

During testing of some organic dielectrics it was noticed that a change in the voltage/stress of breakdown in the dependence on the absorbed radiation dosage takes the form, analogous to a change in the mechanical strength. The investigations, carried out on polyethylene, made it possible to assume that during the study of dielectric strength the decomposition of material can occur due to the mechanical reasons. Electric field causes the compression of sample/specimen only, i.e., creates mechanical load [8].

The interconnection between the electrical and mechanical

strength is observed not always. Thus, in the measurement of the voltage/stress of the breakdown of cellulose-acetate film of up to the radiation dosages  $10^4$  rad there was not noticed definite effects of irradiation on the value of the voltage/stress of breakdown. [51] it is evident from the graphic dependences of a change in the voltage/stress of the breakdown of cellulose-acetate tape in the exposure doses of  $\gamma$ -radiation  $10^4$  and  $10^5$  r (Fig. 3.12) that in these doses the voltage/stress of breakdown in practice does not differ from the values, characteristic for the nonirradiated samples/specimens. However, the mechanical properties of cellulose acetate strongly change in such radiation dosages (see Table 3.1). Similar results were obtained also during the study of the characteristics of fluoroplastic capacitors.

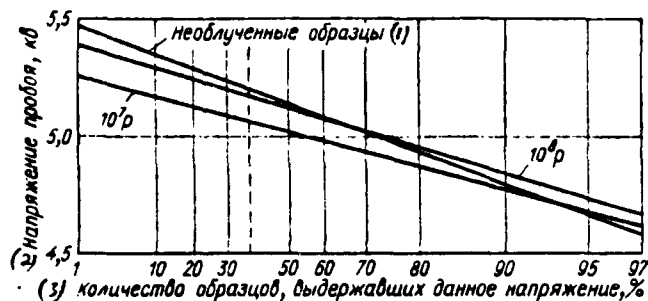


Fig. 3.12. Effect of gamma-irradiation on the value of the voltage/stress of the breakdown of tape from cellulose acetate.

Key: (1). Nonirradiated samples/specimens. (2). Voltage/stress of breakdown, kV. (3). Quantity of samples/specimens, which maintained/withstood this voltage/stress, %.

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Thus, irradiation is actually the supplementary external effect, which can lead in a number of cases to a decrease in the provided for reserve of dielectric strength. This must be considered during the design of equipment and, if it is possible, to increase actual stored up dielectric strength, i.e., to utilize capacitors with the voltage/stress, which it is somewhat less than the established/installed rating.

### 3.6. Change in the mode/conditions of electrical circuit with the capacitor during the pulse irradiation.

The sources of pulse radiation/emission create the usually large of dose rate with a comparatively short time of the effect of radiation/emission. The energy, absorbed by sample/specimen per pulse, does not cause in the majority of the condenser/capacitor materials of noticeable structural changes. Fundamental effects, as a rule, are reversed and connected with a considerable change in the electrical conductivity of dielectrics both during the emission impulse and for a certain period of time after it. The appearance of a supplementary stray current in the capacitor produces change in the mode/conditions of electrical circuit, which depends on the parameters of circuit itself and characteristics of emission impulse.

It is impossible, of course, to examine all cases of applying the capacitors. However, most frequently the capacitors are utilized in the circuits, where direct/constant voltage is applied to them, and variable component is only the small part of this voltage/stress.

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In this case almost any node of an electronic circuit during the time of the radiation pulse can be considered in the form of an equivalent circuit presented in Fig. 3.13. Resistors  $R_1$  and  $R_2$  are specific elements or parameters of the circuit. For example, for the capacitor in the filter of rectifier  $R_1$  - the output impedance of the rectifier, and  $R_2$  - the total impedance of the load. If the capacitor links two cascades/stages of diagram, the  $R_1 = R_{out1} + R_{in1}$ , where  $R_{out1}$  - output resistance of one cascade/stage,  $R_{in1}$  - input resistance of the following cascade/stage;  $R_2$  frequently equal to infinity or is determined by the resistor/resistance of the resistor, shunting capacitor in the diagram.

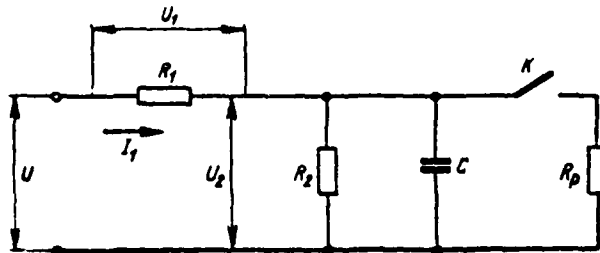


Fig. 3.13. Generalized equivalent diagram of electrical circuit with the capacitor during irradiation.

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For the capacitor in the circuit of automatic shift, feedback, etc.  $R_1$  - output resistance of cascade/stage,  $R_2$  - resistor/resistance of the resistor, which shunted capacitor.

Let us examine the effect of the radiation/emission, the rate of dose of which changes in the form of the step function (on the equivalent diagram this it corresponds to the instantaneous start of key/wrench  $K$ ). We will consider that supplementary leakage resistance of capacitor  $R_{\text{ш}}$  does not depend on time, i.e., the process of the establishment of constant conductivity  $\sigma_{p,y}$  occurs for the time much smaller than the interval of the effect of radiation/emission in question.

Let us assume that the radiation/emission operates only on the capacitor. If in this case a change in the electrical mode/conditions of diagram is comparatively small, then resistors/resistances  $R_1$  and  $R_2$  will have constant value during the irradiation.

Under these assumptions the differential equation of transient process in the diagram in Fig. 3.13 can be recorded in the form

$$\frac{dU_2}{dt} + \frac{U_2}{\tau} = \frac{U}{\tau_1},$$

where  $\frac{1}{\tau} = \frac{1}{\tau_u} + \frac{1}{\tau_p}$ ;  $\frac{1}{\tau_u} = \frac{1}{\tau_1} + \frac{1}{\tau_2}$ ;

$$\tau_1 = CR_1; \quad \tau_2 = CR_2; \quad \tau_p = CR_u.$$

The solution of this equation under the initial conditions  $t=0$

$U_2 = U_0 = U\tau_u/\tau_1$  will be

$$U_2 = U_0 \frac{\tau}{\tau_p} \left( \frac{\tau_p}{\tau_u} + e^{-t/\tau} \right). \quad (3.25)$$

Not an absolute, but relative change in voltage across capacitor

$$\frac{\Delta U}{U_0} = 1 - \frac{U_2}{U_0}. \quad (3.26)$$

is more convenient value. ¶ Substituting in equation (3.26) value of  $U_2$  from formula (3.25), we will obtain

$$\frac{\Delta U}{U_0} = \frac{\tau}{\tau_p} (1 - e^{-t/\tau}). \quad (3.27)$$

If we examine such time interval, in limits of which the condition  $\tau \gg t$  is satisfied, then formula (3.27) is simplified

$$\frac{\Delta U}{U_0} = \frac{t}{\tau_p}. \quad (3.28)$$

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In this case a change of voltage across capacitor is determined by the radiation time constant, which depends only on the parameters of the fundamental dielectric of capacitor. During the pulse irradiation this means that external circuit does not affect a change in the voltage/stress, if the value of complete time constant  $\tau$  is considerably more than the duration of pulse  $t_n$  or taking into account value  $\tau$

$$\tau_n \gg \frac{t_n}{1 - t_n/\tau_p}. \quad (3.29)$$

In this case  $t_n/\tau_p$  it corresponds to a maximum change in voltage across capacitor for the pulse time, i.e., it is equal to value  $\beta = \Delta U/U_0$  with  $t = t_n$ . If capacitor is discharged insignificantly, then  $\beta \ll 1$  and condition (3.29) will pass into inequality  $\tau_n \gg t_n$ .

These conditions frequently are satisfied for the short emission impulses (portion of microsecond - electron accelerators, X-ray tubes, etc.), and therefore capacitor in the diagram can be considered as the isolated/insulated radio part. For example, for the duration of emission impulse  $0.6 \mu s$  a change in voltage on the

capacitors of different types after the termination of impulse/momentum/pulse immediately remained constant, if the time constant of external circuit was more than  $3 \mu\text{s}$  (Fig. 3.14a).

Current in external circuit  $I_1$  (see Fig. 3.13) is the sum of the initial  $I_{10}$  and supplementary  $\Delta I_1$  of currents during the effect of the radiation/emission:

$$I_1 = I_{10} + \Delta I_1; \quad \Delta I_1 = \Delta U / R_1,$$

where  $\Delta U$  it is determined from formula (3.27). The maximum value of circuital current with  $R_1 \rightarrow 0$  is equal the stray current of the capacitor [see formulas (3.22) (3.23)]. After the cessation/discontinuation of irradiation instantaneous component of the induced current becomes equal to zero, but remains delayed component, which with the specific relationships of the parameters of the emission impulse and time constant of external circuit can cause supplementary capacitor discharge.

The relation of instantaneous and delayed components of current at the end of the emission impulse depends on the form of material, duration of pulse and temperature, but it does not depend on the radiation dose rate, since it is assumed that instantaneous and delayed components change relatively to the identical degree with a change in the radiation dose rate (see Chapter 1).

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We will consider for simplicity that delayed component of current drops exponentially with the only time constant  $\tau_{ch}$

$$I_{ch} = I_{ch,0} e^{-t'/\tau_{ch}}, \quad I_{ch,0} = \frac{U_{ch}}{\alpha R_{ch}},$$

where  $t'$  - time ( $t'=0$  it corresponds to the end/lead of the emission impulse);  $U_{ch}$  - voltage across capacitor when  $t=t_n$ ;  $t_n$  - duration of the pulse

$$U_{ch} = U_0 - \Delta U = U_0(1 - \beta).$$

When  $t_n < \tau_{ch}$  [see formulas (3.24) (1.18)] the value of the relation of instantaneous and delayed components of current at the end of the emission impulse

$$\alpha = \frac{\sigma_{p1}^*}{\sigma_{p0}} = \frac{B}{K_3 t_n}. \quad (3.30)$$

A change in voltage across capacitor after the cessation/discontinuation of irradiation will be determined by the following equation:

$$\frac{dU_2}{dt'} + \frac{U_2}{\tau_n} = U_0 \left( \frac{1}{\tau_n} - \frac{1-\beta}{\alpha \tau_p} e^{-t'/\tau_{ch}} \right).$$

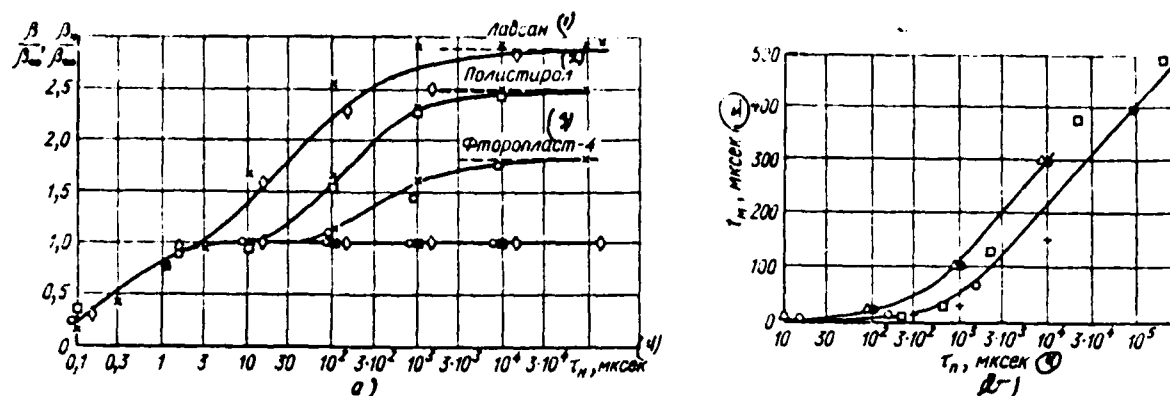


Fig. 3.14. The dependence of voltage across capacitors of different types from the time constant of external circuit during the pulse irradiation: a) the character of a change in the voltage/stress (X - computed values); b) the position of the maximum of a change in voltage on the capacitor ( $\Delta$  - teflon;  $\bullet$  - polystyrene;  $\circ$  - Dacron;  $\square, \times$  - tantalum).

Key: (1). Lavsan. (2). Polystyrene. (3). Teflon. (4).  $\mu\text{s}$ .

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The solution of this equation under the initial condition  $t'=0$ ,  $U_s=U_0$ , takes the form

$$U_s = U_0 \left[ 1 - a e^{-t'/\tau_{en}} + (a - \beta) e^{-t'/\tau_{en}} \right],$$

where  $a = \frac{1 - \beta}{\alpha \tau_p \left( \frac{1}{\tau_n} - \frac{1}{\tau_{en}} \right)}$ ,

or, passing to a relative change in the voltage/stress,

$$\frac{\Delta U}{U_0} = \beta e^{-t'/\tau_n} + a(e^{-t'/\tau_{en}} - e^{-t'/\tau_n}). \quad (3.31)$$

In the particular case when  $\tau_{en}=0$  equality (3.31) leads to the obvious expression for the charge of capacitor through external circuit.

It can grow/rise or decrease depending on the relationship/ratio of the entering formula (3.31) values in the course of time  $(\Delta U/U_0)$ , which is determined by the sign of time derivative of  $(\Delta U/U_0)$  with  $t' \rightarrow 0$ :

$$\frac{d(\Delta U/U_0)}{dt} = \frac{1}{\alpha \tau_p} - \beta \left( \frac{1}{\alpha \tau_p} + \frac{1}{\tau_n} \right).$$

With satisfaction of the condition

$$\beta > \frac{1}{1 + \alpha \tau_p / \tau_n} \quad (3.32)$$

the derivative has negative value, which corresponds to the absence of supplementary discharge.

Under the given conditions for irradiation there is certain boundary value of the time constant of external circuit. With  $\tau_n$  smaller than this value, the capacitor is discharged only during the emission impulse. Increase  $\tau_n$  leads to the supplementary capacitor

discharge after the cessation/discontinuation of irradiation.

If  $\beta = t_0/\tau_p \ll 1$ , then taking into account of condition (3.32) and value  $\alpha$  (3.30) we will obtain

$$\tau_{n, rp} = B/K_3. \quad (3.33)$$

It should be noted that condition (3.32) can be obtained also from the simple comparison of the currents of charge and capacitor discharge at the moment of the cessation/discontinuation of pulse of radiation/emission. Consequently, this condition is correct with any form of decay in the induced conductivity.

Let us determine the time, with which must be observed the maximum value  $\Delta U/U_0$ , if capacitor additionally is discharged after impulse/momentum/pulse. Assuming/setting by the equal to zero first time derivative of formula (3.31), we will obtain

$$t_m = \frac{\tau_{cn}}{1 - \tau_{cn}/\tau_n} \ln \left[ \frac{\tau_{cn}}{\tau_n} + \frac{\beta}{(1 - \beta)} \frac{\alpha \tau_p}{\tau_n} \left( 1 - \frac{\tau_{cn}}{\tau_n} \right) \right]^{-1}. \quad (3.34)$$

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The value of a maximum change in voltage across capacitor can be determined, substituting the value  $t_m$  from formula (3.34) in formula (3.31)

$$\beta_M = \left( \frac{\Delta U}{U_0} \right)_M = (1 - \beta) \frac{\tau_M}{\alpha \tau_p} \left[ \frac{\tau_{cn}}{\tau_M} + \frac{\beta}{(1 - \beta)} \times \right. \\ \left. \times \frac{\alpha \tau_p}{\tau_M} \left( 1 - \frac{\tau_{nc}}{\tau_M} \right) \right]^{\frac{1}{1 - \tau_{cn}/\tau_M}}. \quad (3.35)$$

For the separately undertaken capacitor when  $\tau_M \rightarrow \infty$  from relationship/ratio (3.35) it follows

$$\beta_{M\infty} = \beta_\infty + (1 - \beta_\infty) \frac{\tau_{cn}}{\alpha \tau_p}.$$

If moreover,  $\beta = \tau_M/\tau_p \ll 1$ , then

$$\beta_{M\infty} = \beta_\infty \left( 1 + \frac{\tau_{cn}}{\alpha \tau_M} \right). \quad (3.36)$$

Value  $\beta_{M\infty}$  characterizes the greatest change in voltage across capacitor, which occurs both during the emission impulse and after it.

The effect of delayed component of radiation current is convenient to characterize by the relation

$$\frac{\beta_{M\infty}}{\beta_\infty} = 1 + \tau_{cn} \frac{K_2}{B} \approx 1 + \frac{bK_3}{B\rho^0}, \quad (3.37)$$

which is obtained from formulas (3.36) (3.30) and (1.20).

The time constant of decay  $\tau_{cn}$  is  $10^{-3}$ - $10^{-4}$  s at the radiation dose rate  $10^5$ - $10^7$  r/s, and relation  $B/K_2 = 10^{-4}$ - $10^{-5}$  s. It follows from given data that the relative contribution of delayed component can reach the high values:  $\beta_{M\infty}/\beta_\infty = 4$ -20. An increase in the radiation dose

rate leads to the decrease of this relation. Table 3.7 and Fig. 3.14a give the results, obtained on the linear electron accelerator at the rate of dose  $4 \cdot 10^{10}$  r/s  $\left( t_{\mu} = 0,6 \mu s \right)$ . In this the case delayed component causes much the same capacitor discharge as instantaneous component of induced conductivity.

Table 3.7. Relative effect of delayed component on the capacitor discharge.

(1) Материал	$\beta_{M\infty}/\beta_{\infty}$
Оксид тантала (2)	2,5—4
Лавсан (3)	~3
Полистирол (4)	2,5
Фторопласт-4 (5)	1,8
Слюда (6)	0

Key: (1). Material. (2). Oxide of tantalum. (3). Lavsan. (4). Polystyrene. (5). Teflon. (6). Mica.

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The effect of the delayed comprising induced conductivity can be developed also in the form of an increase in the recovery time on the capacitor. Usually this time is determined by the duration of charge of capacitor through external circuit with the time constant  $\tau_M$ . Restoration/reduction begins immediately after the cessation/discontinuation of irradiation. If capacitor continues to be discharged after emission impulse, then resumption of voltage will be begun only after time  $t_M$  [see formula (3.34)] after the end/lead of the impulse/momentum/pulse it will be more prolonged.

An increase in recovery time can be rated/estimated from comparison  $t_M$  and  $\tau_M$ . For simplicity let us examine frequently

encountered case  $\beta = t_M/\tau_M \ll 1$ . Above it was shown that the supplementary capacitor discharge occurs under condition  $\tau_M > \tau_{M,rp}$ . If we determine  $\tau_{M,rp}$  from formula (3.37) taking into account (3.33), then this condition will take the following form:

$$\frac{\tau_{cn}}{\tau_M} < (\beta_{M\infty}/\beta_{\infty} - 1).$$

At the large radiation dose rate the value, which stands in the right side of the inequality, is close to one (Table 3.7). At the smaller dose rate it can be more than one, but nevertheless for the sufficiently slow responses of external circuit  $\tau_M$  in the first approximation, correctly  $\tau_{cn}/\tau_M \ll 1$ . Then equation (3.34) can be simplified

$$t_M/\tau_{cn} \approx \ln(\tau_M/\tau_{cn}).$$

It is evident from this expression that  $t_M \leq \tau_M$ . Consequently, in many instances the supplementary delay of the restoration/reduction of the mode/conditions of electrical circuit with the capacitor is not essential. Fig. 3.14b gives experimental dependences  $t_M$  on the time constant of external circuit for the different types of capacitors. Irradiation was conducted by the single momentum of an electron of linear accelerator with a duration of  $0.6 \mu s$  and by the rate of the dose  $4 \cdot 10^{11}$  of r/s. Under these conditions only with comparatively fast time constants of external circuit ( $10-30 \mu s$ )  $t_M$  is compared with  $\tau_M$ . In the remaining cases the delay of the

restoration/reduction of the mode/conditions of diagram comprises less than 10% usual time of the establishment of steady state.

When external resistance is very great  $(\tau_{\text{ex}} \rightarrow \infty)$ , it is possible to rate/estimate a change in voltage across capacitor in the more general view, for any form of emission impulse [44].

The current, which causes capacitor discharge, is determined by formula (3.23) taking into account formulas (1.15) (1.16) (1.19)

$$I_c = -I_p = CUK_n P^A + \sum_{i=1}^n CUK_{s,i} \int_0^t P^A(t') e^{-(t-t')/\tau_{\text{cn}}} dt'.$$

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Let us assume  $\Delta=1$  and we will consider that a change in the voltage/stress does not depend on capacitance value of capacitor. Then equation for changing the voltage/stress is recorded in the following form

$$\frac{dU}{dt} = -U \left[ K_n P + \sum_{i=1}^n K_{s,i} \int_0^t P(t') e^{-(t-t')/\tau_{\text{cn}}} dt' \right]. \quad (3.38)$$

If delayed component of the induced current has only one component ( $n=1$ ), then, by integrating equation (3.38) for the time from 0 to  $\infty$ , we will obtain

$$\ln \frac{U_{\infty}}{U_0} = -K_n D - \lim_{t \rightarrow \infty} K_s \int_0^t \int_0^x P(t') e^{-(x-t')/\tau_{\text{cn}}} dt' dx, \quad (3.39)$$

where  $U_{\infty} = \lim_{t \rightarrow \infty} U$  and  $D = \int_0^{\infty} P dt$  — complete absorbed radiation dosage.

Solving the second term in expression (3.39) with the aid of the Laplace transform, we will obtain the value of voltage interesting us across capacitor [44]:

$$U_{\infty} = U_0 e^{-D(K_M + K_3 \tau_{cu})}$$

or, if we switch over to a relative change in the voltage/stress,

$$\frac{\Delta U}{U_0} = 1 - e^{-D(K_M + K_3 \tau_{cu})}. \quad (3.40)$$

With the rectangular form of emission impulse  $D = t_u P$ . After designating  $K_M + K_3 \tau_{cu} = B$  (or with the insignificant effect of delayed component  $B \approx K_M$ ),

we will obtain the exponent of exponential curve from equation (3.40) in the form  $t_u B P$ . Taking into account that formula (3.40) is obtained for  $\Delta = 1$ , it is possible to record  $B P = 1/\tau_p$ . Consequently,

$$\frac{\Delta U}{U_0} = 1 - e^{-t_u/\tau_p},$$

which completely coincides with formula (3.27) when  $\tau_{cu} \rightarrow \infty$ .

The important consequence of the calculations conducted for the isolated/insulated capacitor is the dependence of a change in the voltage/stress on it from the dose with any form of emission impulse. This considerably simplifies practical evaluations/estimates according to the effect of pulse radiation/emission on the capacitors, since usually dose most easily yields to measurement and

theoretical forecasting. However, it is necessary to remember that the computations examined are made for  $\Delta=1$ . If  $\Delta$  is less than one, then, obviously, will be obtained the strongly high result with respect to a change in the voltage/stress, and, the greater the radiation dose rate and is the less  $\Delta$ , the fact error will be more.

The calculated evaluation/estimate of the absorbed radiation dosages, in which occurs a relative change in voltage across capacitors on 10, 63 and 90%, is given in Table 3.8 [44].

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Thus, on the basis of the experimental results with respect to a change in the conductivity of electrical insulating materials, it is possible to rate/estimate the special features/peculiarities of the behavior of capacitor in the radio-electronic diagrams. This makes it possible to create the procedure of the calculated forecasting of the radiation stability of multicomponent nodes and units of equipment with the use of computer technology.

A practical selection of the type of capacitor and value its capacitance are determined by the requirements, presented to this node of radio-electronic device/equipment and by radiation conditions. One and the same capacitor can, for example,

comparatively little change the parameters from the radiation dosage, but have the high strength of induced current of leak/leakage. Therefore for the capacitors it is difficult to indicate the single criterion of radiation stability and virtually it is not possible in general form to arrange different types of capacitors according to the degree of the effect on them of irradiation. In each specific case should be considered all conditions for the work of capacitor, in order to select the most adequate/approaching type of capacitor and the value of its capacitance.

Table 3.8. Change in voltage across capacitors of different types during irradiation.

(1) Конденсатор	$K_M + K_{\Sigma \text{сп}}$ (2) (rad) $^{-1} 10^{-4}$	(3) Доза при изменении напряжения, Mrad		
		(4) на 10%	(5) на 50%	(6) на 90%
Керамический (7)	0,032	0,31	3,1	7,2
Стекл.янный (8)	1,5	0,0067	0,067	0,15
Слюдяной (9)	0,42	0,024	0,24	0,55
Лавсановый (10)	0,45	0,023	0,23	0,51
Танталовый (11)	0,36	0,028	0,28	0,64
Полистироловый (12)	0,3	0,033	0,33	0,77

Key: (1). Capacitor. (2). rad. (3). Dose with change in voltage/stress, Mrad. (4). on. (5). Ceramic. (6). Glass. (7). Mica. (8). Dacron. (9). Tantalum. (10). Polystyrene.

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#### Chapter 4.

Procedure of the experimental studies of resistors and capacitors on different sources of the ionizing radiation/emission.

##### 4.1. Special features/peculiarities of procedure.

One of the fundamental methods of obtaining the reliable information about the radiation stability of the elements/cells of radio-electronic equipment, including resistors and capacitors, are tests on different sources of the ionizing radiations/emissions, which most fully imitate possible operating conditions.

For testing of radio-electronic equipment, elements/cells and materials are utilized such sources of radiation as pulse and static nuclear reactors on the thermal, intermediate and fast neutrons, generators of the powerful/thick impulses/momenta/pulses of X-radiation and different kind the electron accelerators, protons and

other elementary particles. Tables 4.1 and 4.2 give the fundamental characteristics of the pulse and static reactors of the USA [32, 46-49]. The possible conditions, created during the thermonuclear blasts, are given in Fig. 1.1.

Table 4.1. Fundamental characteristics of pulse nuclear reactors of the USA.

(1) Реактор	(2) Поток нейтронов за импульс, нейтрон/см <sup>2</sup>	(3) Максимальная мощность дозы γ-излучения, р/сек	(4) Длительность им- пульса на половине амплитуды, мкс
Godiva I	$>2,5 \cdot 10^{13}$	$>10^7$	50
Godiva II	$>2,5 \cdot 10^{13}$	$>10^7$	40+50
Triga	$1 \cdot 10^{14}$	$3 \cdot 10^6$	10 <sup>4</sup>
FBP	$1 \cdot 10^{14}$	—	40
Sandia	$1 \cdot 10^{13}$	$2 \cdot 10^6$	50
Molli-G	$2 \cdot 10^{14}$	—	50
Kukla	$1,4 \cdot 10^{14}$	$10^9 + 10^{10}$	60
ORN-I	—	$\sim 10^6$	—
GEPR	$7 \cdot 10^{13}$	$7,4 \cdot 10^6$	38
APPA	$\sim 10^{13}$	—	<40

Key: (1). Reactor. (2). Neutron flux per pulse, neutrons/cm<sup>2</sup>. (3). Maximum rate of dose of γ-radiation, r/s. (4). Pulse duration on half of amplitude, μs.

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The use/application of measuring equipment for remote control with the units of automatic recording and removing/taking the information is the specific special feature of the methods for testing radio-electronic equipment and its elements/cells in the fields of the ionizing radiations/emissions. The creation of this measuring equipment runs into a whole series of the difficulties, to number of which should be related: a) the difficulty of measuring of the separate parameters and characteristics by remote/distance

methods; b) the need for utilizing the information circuits, immune to the effect of radiation and electromagnetic focusings/inductions; c) the high rates of the effect of pulse radiation and instantaneous changes in the electrical parameters of the elements/cells of equipment; d) the impossibility of adjustments and repairing the measuring ones of device/equipment in the field of radiation.

The existing measuring equipment, as is known, makes it possible to measure the majority of the fundamental parameters of radio-electronic equipment and its elements/cells, but it is not designed for the carrying out of telemetering and measurements of short-term changes in the electrical parameters with the automatic recording. All this requires the development of special test equipment with the limited use of the serially produced instruments.

Let us pause at the methods for testing resistors and capacitors during the pulse and prolonged irradiation.

Table 4.2. Fundamental characteristics of the static sources of penetrating radiation.

(1) Источник	(2) Максимальная плотность потока нейтронов, нейтрон/(см <sup>2</sup> ·сек)	(3) Максимальная мощ- ность дозы γ-излучения, р/сек	(4) Мощность реактора, Мвт
(5) Реактор FNR (6) канал D	(7) 2,7·10 <sup>13</sup> , тепловые 2,5·10 <sup>13</sup> , E>0,5 Мэв(8) 7,2·10 <sup>13</sup> , E>2,9 Мэв 2,3·10 <sup>13</sup> , E>5,3 Мэв 3,9·10 <sup>13</sup> , E>8,6 Мэв	1,2·10 <sup>8</sup>	1
(5) Реактор CP-5	10 <sup>8</sup> , E>2,5 Мэв(8) 5,4·10 <sup>8</sup> , E>1 Мэв(8) 2,4·10 <sup>13</sup> , тепловые(7)	0,75·10 <sup>8</sup>	2
(5) Реактор MTR	2·10 <sup>14</sup> , тепловые(7) 1,3·10 <sup>13</sup> , E>1 Мэв(8)	10 <sup>8</sup>	40

Key: (1). Source. (2). Maximum neutron flux density, neutron(cm<sup>2</sup>·s).  
 (3). Maximum rate of dose of γ-radiation, r/s. (4). Power of reactor,  
 MW. (5). Reactor. (6). (channel D). (7). thermal. (8). MeV.

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#### 4.2. Procedure of the experimental studies of radio parts on the pulsed sources of penetrating radiation.

The procedure of the experimental studies of radio parts under the effect of pulse irradiation decomposes into two parts, connected with the need recording the change of their parameters directly at the moment of acting the impulse/momentum/pulse of radiation

(temporary/time changes, which disappear with the cessation/discontinuation of irradiation) and recording of the residual/remanent changes in the parameters, which are preservable after the effect of the impulse/momentum/pulse of radiation. The greatest difficulties appear during recording of short-term changes in the parameters.

The special feature/peculiarity of the procedure of recording temporary/time changes in the ohmic resistance of resistors and insulation resistance of capacitors during the testing on pulse reactors is the remote/distance recording of signals, which is conjugated/combined with the need for the transmission of the current pulse of short duration (from several microseconds to several milliseconds) with the aid of 10-20-meter cable from the tested radio parts to registering apparatus, and also the remote photographing of signal from the oscilloscope face. As an example Fig. 4.1a gives the block diagram of the circuit of recording a change of resisting of resistors and current of the leak/leakage (insulation resistance) of capacitors in the process of irradiation on the pulsed sources.

The fundamental requirements, presented to the test procedure, to the measuring and accessories, are reduced: to the guarantee of transmission and to the reception of information at a distance of 10-30 m; the complete automation of the process of measurements and

recording; the necessary resolution of measuring and recorders; to the shadowing of measuring circuit and experienced/tested radio parts from the effect of electromagnetic focusings/inductions.

For meeting of these requirements registering apparatus (oscillographs) and as far as possible accessories they are placed in the specially equipped measuring laboratories, carried out from radiation zone and shielded from the direct effect of  $\gamma$ -neutron radiation/emission.

For the protection from electromagnetic focusings/inductions the tested radio parts connect with the equipment for recording, as a rule, by shielded coaxial cables; but sometimes, as an exception, can be used twin-lead symmetrical wiring. Provision is made for also the common grounding of entire metering circuit at one point, it is usually direct at the input of oscillograph.

The test specimens are unsoldered with the aid of coaxial cables and are fastened on the special table-holder or other devices/equipment, which are arranged/located at different distances from the center of the source of the ionizing radiation/emission, for example reactor core. The possibility of the simultaneous investigation of radio parts under the influence on them of radiation/emission with different dose rate is reached thereby.

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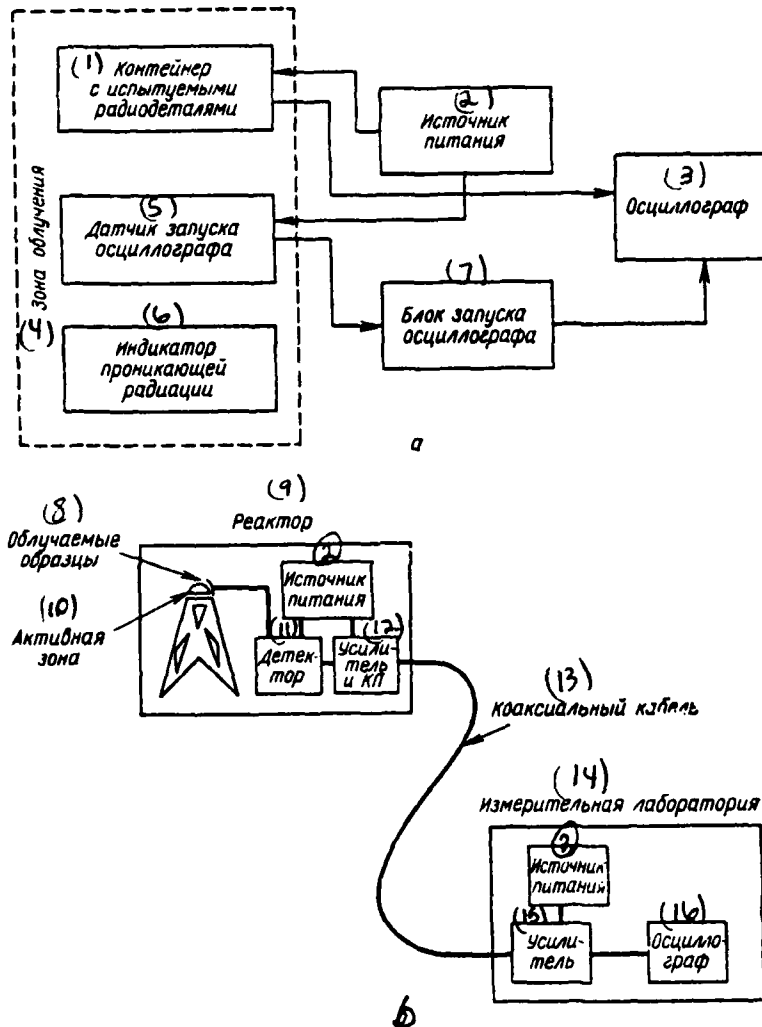


Fig. 4.1. Block diagram of equipment for recording temporary/time changes in parameters of radio parts (a) and exemplary/approximate schematic of layout of equipment at their irradiation (b) on pulsed

sources of radiation/emission.

Key: (1). Container with the tested radio parts. (2). Power supply. (3). Oscillograph. (4). Radiation zone. (5). Sensor of starting/launching of oscillograph. (6). Indicator of penetrating radiation. (7). Unit of starting/launching of oscillograph. (8). Irradiated samples/specimens. (9). Reactor. (10). Active region/core. (11). Detector. (12). Amplifier and KP. (13). Coaxial cable. (14). Measuring laboratory. (15). Amplifier. (16). Oscillograph.

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To avoid supplementary leaks/leakages by ionized air of the place of the unsoldering of radio parts, and also all cable connections shield by different compounds (most frequently by paraffin). The exemplary/approximate schematic of layout of equipment during irradiation of radio parts on the pulse reactors is given in Fig. 4.1b [18, 29]. As recorders multichannel electron oscillographs are utilized in essence.

One of the difficulties, which appear during the remote/distance recording of a change of resisting of resistors or insulation resistance of capacitors, the need for the transmission of the current pulse, caused by a change in resistance, with the minimum

distortion of form. In connection with this it is necessary to consider the effect of the parameters of coupling cable on the time constant of the circuit of recording. Fig. 4.2 depicts fundamental and the equivalent circuit diagrams of recording a change in the resistor/resistance during the pulse irradiation.

Since the insulation resistance of cable  $R_{\text{ins.k}}$  even taking into account the fact that it descends under the effect of the impulse/momentum/pulse of radiation, considerably higher than resistor/resistance of the descent of the recording oscillographs ( $R_{\text{ex.occ}}$  order of hundreds of ohms, to 0.5 MΩ) and the ohmic resistance of cable ( $R_k$  the order of 10 ohms) in all cases is considerably lower than the resistor/resistance of the tested resistors, effect  $R_{\text{ins.k}}$  and  $R_k$  on the time constant of the circuit of recording is very insignificant. The capacitance of the input of oscillographs ( $C_{\text{in}}$  the order of several ten picofarads) also it is possible not to consider, since it is much less than the capacitance of coupling cable. Therefore the equivalent circuit diagram of recording can be simplified and represented in the form of parallel connection of the capacitance of cable and resistor/resistance  $R_s(t)$ :

$$R_s(t) = \frac{R_x(t) R_{\text{ex}}}{R_x(t) + R_{\text{ex}}}, \quad (4.1)$$

where  $R_x(t)$  - resistor/resistance of article at the moment of irradiation;  $R_{\text{ex}}$  - input resistance of the recorder.

These diagram (Fig. 4.2d) can be considered as the integrating chain/network, for which the condition for the transmission of current pulse with the minimum distortion of form is expressed by relationship/ratio  $t \gg R_0 C$ , where  $t$  - duration of emission impulse;  $R_0 C = \tau$  - time constant of the circuit of recording.

Virtually, if the duration of emission impulse on one-two orders is more than the time constant of the circuit of recording, then the distortions of the form of current pulse are very insignificant. Based on this condition it is conducted the selection of the constant value of the time of the circuit of recording during the experimental investigations of radio parts on the pulsed sources of penetrating radiation.

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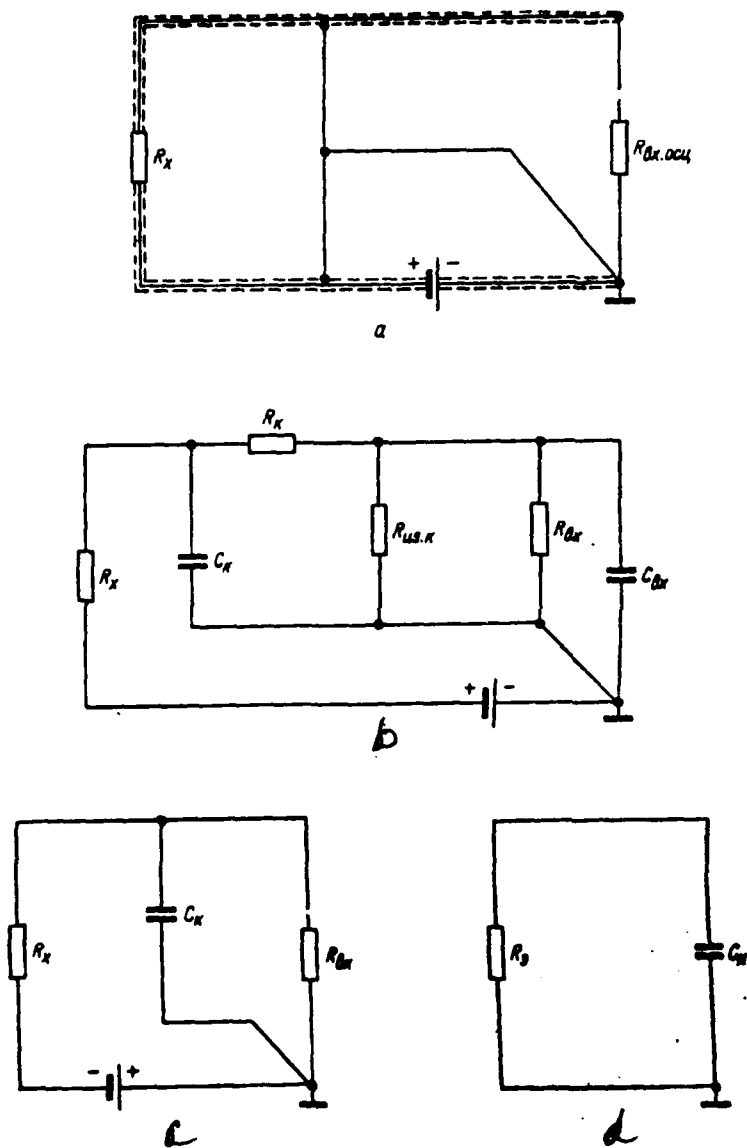


Fig. 4.2. Fundamental (a) and equivalent diagrams (b, c, d) of circuit of recording change in resistor/resistance during irradiation

at impulse reactors.

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If necessary of studying the character of decay in the current it is necessary to provide several ranges of time and sensitivity for recording this process.

The measurement of capacitance of capacitors during the pulse irradiation is complicated by the fact that not always it is possible to utilize usual frequency response methods of measurements. The measurement of the loss tangent under these conditions even is more problematic. With the short emission impulses it is possible to utilize only sufficiently high frequency of alternating voltage so that the period of oscillation of voltage/stress would be much less than the pulse duration. A change in capacitance and loss tangent of low-frequency capacitors (in the usual understanding) generally cannot be measured on the sources of pulse radiation/emission, which have the short pulse duration.

Residual/remanent changes in the parameters of resistors and condensers are rated/estimated by measuring their fundamental parameters (resistor/resistance, temperature specific resistance, emf of the noises of resistors, and also capacitance, loss tangent and

insulation resistance of capacitors) before and after pulse irradiation. These measurements, as a rule, are made on the standard measuring meters.

When is possible the formation/education of radioactive isotopes in the materials of radio parts, it is necessary to consider the level of the induced activity and, if it exceeds the permissible norms, to observe the usual safety regulations with the work with such elements/cells.

#### 4.3. Procedure of the experimental studies of radio parts on the static sources of penetrating radiation.

During the tests of resistors and capacitors in the channels of nuclear reactors or in radiation zone of other sources on them simultaneously affect radiant flux, the temperature, the humidity and the ionized environment. In connection with this appear the difficulties during the determination of a change in the parameters only from the effect of the penetrating radiations/emissions. In order to eliminate the effect of humidity and ambient temperature on the parameters of elements/cells, the latter it is necessary to place in the hermetically sealed containers with conditioned air. The effect of the ionization of medium is removed via the filling of the open contacts of parts by different compounds.

The programs of experimentation on the static radiation sources usually rely on obtaining of the greatest quantity of information at the moment of the effect of radiation/emission. The radio parts, intended for the investigation, are assembled into the special cases (containers), whose sizes/dimensions correspond to the sizes/dimensions of experimental channels and chambers/cameras of radiation sources.

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The measurement of the parameters of resistors and capacitors in the process of prolonged irradiation is made remotely/distance. Measuring equipment is arranged/located in the special measuring laboratories out of radiation zone. The distance between the test specimens and the measuring equipment is 15-50 m usually. The part of the coupling cable (2-3 m) is located directly in the zone of acute irradiation; therefore with the estimate of the magnitude of a change in the parameters of articles it is necessary to search for ways for the exception/elimination of the effect of a change in the parameters of cable to the value of the measured parameters.

The need for the monitoring of the parameters of the same-type

samples/specimens of articles in the identical of conditions of irradiation, i.e., during the short time when substantially they did not change dose, temperature, etc., forces to apply different automatic measuring devices.

Thus, fundamental requirements for the methods of measuring the parameters of resistors and capacitors in the process of prolonged  $\gamma$ - and neutron irradiation can be formulated as follows: a) the guarantee of transmission and reception of information at a distance of 20-50; b) the sufficiently high rate of measurements; c) exception/elimination or the account of the supplementary errors, caused by changes in the parameters of the lines of communications, which undergo the effect of radiation, and also by changes in the temperature as a result of the radiation heating.

Let us examine some possible diagrams and special features/peculiarities of the measurement of the separate parameters of resistors and capacitors.

In the process of prolonged  $\gamma$ - and neutron irradiation in fixed resistors is made the measurement of ohmic resistance, in variable/alternating resistors - measurement of the established/installed resistor/resistance (for checking the reliability of contact throughout the entire length of conducting

layer is installed slipring contact to  $1/4$ ,  $1/2$  and the complete value of nominal resistor/resistance), and also the insulation resistance between the conducting element and the housing.

Simultaneously with the measurement of the electrical parameters is checked the temperature of the medium, which surrounds resistors, and also the temperature of the surface of resistors with the aid of copper-constantan or other thermocouples. The block diagram of measurements is shown in Fig. 4.3a. As the measuring meters are utilized standard resistance bridges with the galvanometers or the chart-recording instruments, and also automatic resistance bridges. The connection of the tested resistors with the measuring bridges is accomplished/realized with the aid of the multiple shielded cable. The special switching devices/equipment are utilized for the successive connection of the test specimens to the measuring systems.

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The tests of resistors perform both in the unloaded (passive) state and under the electrical load up to the nominal (in this case to the period of the measurement of resistor/resistance resistors they are disconnected from the power supply they are located under the voltage of measuring bridge).

The equivalent measuring circuit of the resistor/resistance of

resistors in the process of prolonged irradiation is given in Fig.

4.3b. The account of the effect of the measurement of the parameters of cable on magnitude of the change of resistance the resistors makes it possible in the majority of the cases to disregard/neglect this effect, since the supplementary error in this case does not exceed 1%, which is completely admissible during the evaluation/estimate of a change of resisting the resistors.

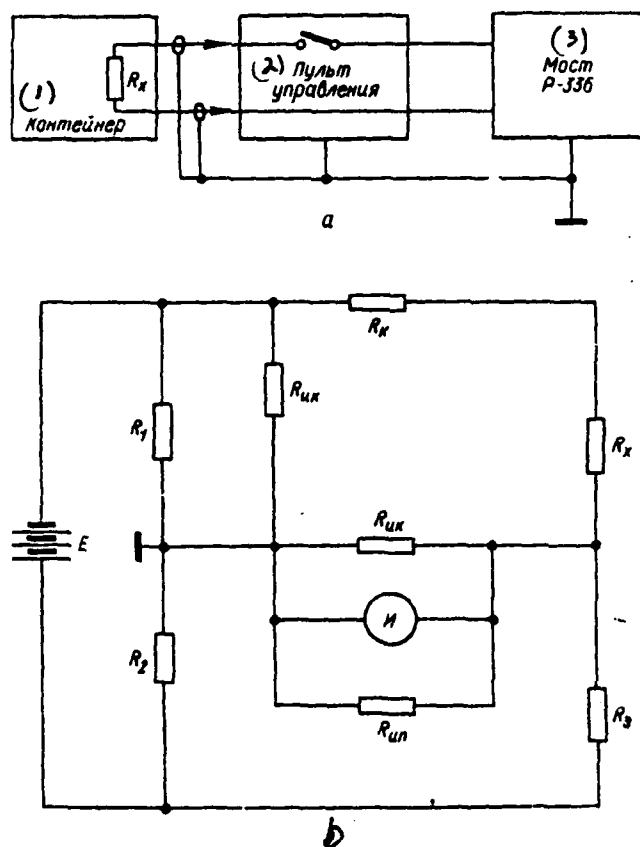


Fig. 4.3. Block diagram of measurement (a) and the equivalent circuit diagram of recording the resistor/resistance of resistors (b) during irradiation on the static sources.

Key: (1). Container. (2). Control panel. (3). Bridge P-336.

In capacitors is measured the capacitance, the loss tangent (most frequently at the frequency of 1 kHz) and insulation resistance (stray current) with direct/constant voltage.

In contrast to the resistors the cable line is serious interference in the measurements of all parameters of capacitors. Usual measuring meters do not make it possible to carry out telemetering with the long line of communications, especially with a change of the characteristics of junction as a result of radiation effect.

The existing capacitance bridges can be utilized only during the study of the irreversible phenomena in the capacitors after the effect mainly of  $\gamma$ -radiation. Irradiation by neutrons leads to sample/specimen activation, and with the flows  $10^{13}$ - $10^{15}$  neutrons/cm<sup>2</sup> is usually necessary special protection for the work with the irradiated samples/specimens and as consequence - telemetering of the parameters of capacitors.

Virtually during the study of the radiation stability of capacitors it is necessary to use the instruments, specially developed for these purposes. This makes it possible to carry out the

measurement even of the residual phenomena under any conditions, necessary for experimenter.

The principles of the construction of remote/distance meters are based on the inclusion/connection of junction in parallel to the low-resistance arms of bridge circuit or on the automatic maintenance of the voltage/stress between the habitable and the screen/shield of the line of communications, close to zero. As an example of this diagram it is possible to give bridge with the transformer arms (Fig. 4.4).

During capacitor testing of the great capacity (tens of thousands of picofarads and more) the measurements of the loss tangent are complicated by the effect of the ohmic resistance of the vein/strand of coupling cable. In order to decrease this effect, it is necessary to utilize wires with the sufficiently large cross section of vein/strand.

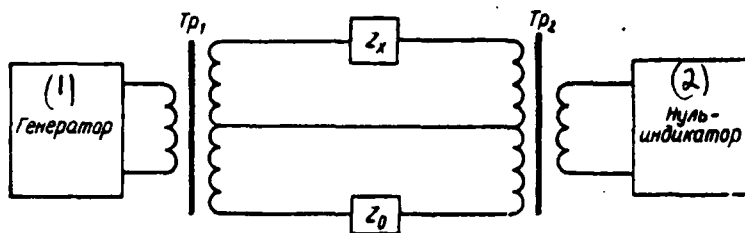


Fig. 4.4. Bridge circuit of alternating current with the transformer arms.

Key: (1). Generator. (2). Null indicator.

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Furthermore, in the measuring meter is introduced the special compensation, which makes it possible to obtain the results of measurements in the undistorted form.

The measurement of insulation resistance is made according to the diagram, analogous to Fig. 4.3a. In this diagram in principle it is possible to utilize the usual mega-ohmmeters, intended for characteristic measurement of electrical insulating materials. However, in the mega-ohmmeters are applied the high-impedance elements/cells, which frequently do not make it possible to get rid of the effect of junction on the results of measurements. Therefore

in the measurement of the insulation resistance of capacitors to more conveniently use the method of voltmeter - ammeter. In this case this method makes it possible to select sufficiently low-resistance galvanometer or electrometric amplifier with the low input resistance and to conduct measurements with the voltages of equal value and polarity.

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# Appendix 1.

## System of the abbreviations of resistors [35].

(1) Постоянные резисторы	(2) Переменные резисторы	(3) Вид резисторов
C1	СП-1	(4) Непроволочные поверхностные углеродистые и бороуглеродистые
C2	СП-2	(5) Непроволочные поверхностные металлопленочные и металлоокисные
C3	СП-3	(6) Непроволочные поверхностные композиционные
C4	СП-4	(7) Непроволочные объемные композиционные
C5	СП-5	(8) Проволочные

Key: (1). Fixed resistors. (2). Variable/alternating resistors. (3). Type of resistors. (4). Non-wire surface carbonic and boron-carbon. (5). Non-wire surface metal-film and metal-oxide. (6). Non-wire surface composite. (7). Non-wire volumetric composite. (8). Wire.

## System of the abbreviations of capacitors [45].

First index: K - capacitor of constant capacitance.

The second index:

10 - ceramic to the nominal voltage/stress is below 1600 V.

15 - ceramic by the nominal voltage/stress 1600 V is higher.

21 - glass.

22 - glass-ceramic.

23 - glass-enamel.

31 - mica small power.

32 - mica large power.

40 - paper to the nominal voltage/stress is below 1600 V with the foil facings.

41 - paper by the nominal voltage of 1600 V and higher with the foil facings.

42 - paper with the metallized facings.

50 - electrolytic aluminum.

51 - electrolytic tantalum foil.

52 - electrolytic tantalum bulk porous.

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53 - oxide-semiconductor.

60 - air.

61 - vacuum.

70 - polystyrene with the foil facings.

71 - polystyrene with the metallized facings.

72 - teflon.

73 - Dacron with the metallized facings.

74 - Dacron with the foil facings.

75 - combined.

76 - varnish-film/lacquer-film.

The third and fourth indices designate designation/purpose and version of the performance of the capacitors of one group according to the type of dielectric.

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## Appendix 2.

Conversion table of ones measurement.

(1) Наименование величин	(2) Система единиц	(3) Единицы измерения	(4) Сокращенное обозначение	(5) Коэффициент для приведения к единицам СИ
(6) Активность изотопа в радиоактивном источнике	(7) СИ Внесистемная единица	(8) Распад в секунду (9) Кюри	(10) расп/сек (11) Кюри	1 (12) Кюри = $3,700 \cdot 10^{10}$ расп/сек (13)
(14) Поток нейтронов или $\gamma$ -квантов	СИ (15) СГС Внесистемная единица	(16) Нейтрон ( $\gamma$ -квант) на квадратный метр (17) Нейтрон ( $\gamma$ -квант) на квадратный сантиметр (18) Только для потока нейтронов	(19) нейтрон/м <sup>2</sup> , $\gamma$ /м <sup>2</sup> (20) нейтрон/см <sup>2</sup> , $\gamma$ /см <sup>2</sup> nvt	— (21) 1 нейтрон/см <sup>2</sup> = $1 \cdot 10^4$ нейтрон/м <sup>2</sup> (22) 1 $\gamma$ /см <sup>2</sup> = $1 \cdot 10^4$ $\gamma$ /м <sup>2</sup> (23) 1 nvt = $1 \cdot 10^4$ нейтрон/м <sup>2</sup> (24)
(25) Плотность потока нейтронов или $\gamma$ -квантов	СИ (26) СГС Внесистемная единица	(27) Нейтрон ( $\gamma$ -квант) на квадратный метр (28) Нейтрон ( $\gamma$ -квант) в секунду на квадратный сантиметр (29) Только для потока нейтронов	(30) нейтрон/(сек·м <sup>2</sup> ) (31) $\gamma$ /(сек·м <sup>2</sup> ) (32) нейтрон/(сек·см <sup>2</sup> ) (33) $\gamma$ /(сек·см <sup>2</sup> ) nv	— (34) 1 нейтрон/(сек·см <sup>2</sup> ) = $1 \cdot 10^4$ нейтрон/(сек·м <sup>2</sup> ) (35) 1 $\gamma$ /(сек·см <sup>2</sup> ) = $1 \cdot 10^4$ $\gamma$ /(сек·м <sup>2</sup> ) (36) 1 nv = $1 \cdot 10^4$ нейтрон/(сек·м <sup>2</sup> ) (37)
(38) Поток энергии нейтронов или $\gamma$ -квантов	СИ (39) СГС Внесистемная единица	(40) Джоуль на квадратный метр (41) Эрг на квадратный сантиметр (42) Электронвольт на квадратный сантиметр	(43) дж/м <sup>2</sup> (44) эрг/см <sup>2</sup> (45) эв/см <sup>2</sup>	— (46) 1 эв/см <sup>2</sup> = $1 \cdot 10^{-19}$ дж/м <sup>2</sup> (47) 1 эрг/см <sup>2</sup> = $1 \cdot 10^{-7}$ дж/м <sup>2</sup> (48) 1 эв/см <sup>2</sup> = $1,6 \cdot 10^{-19}$ дж/м <sup>2</sup> (49)

(21) Интенсивность излучения (плотность потока энергии)	СИ СГС (2) Внесистемная единица	(28) Ватт на квадратный метр (31) Эрг в секунду на квадратный сантиметр (33) Электронвольт в секунду на квадратный сантиметр	вт/м <sup>2</sup> (29) эрг (сек·см <sup>2</sup> ) (32) эв (сек·см <sup>2</sup> ) (34)	— 1 эрг (сек·см <sup>2</sup> ) = 1·10 <sup>-3</sup> вт/м <sup>2</sup> (29) 1 эв/(сек·см <sup>2</sup> ) = 1,6·10 <sup>-13</sup> вт/м <sup>2</sup> (29)
(35) Поглощенная доза излучения	СИ (7) СГС Внесистемная единица	(36) Джоуль на килограмм (38) Эрг на грамм (40) рад	дж/кг (37) эрг/г (39) рад (40)	— 1 эрг/г = 1·10 <sup>-4</sup> дж/кг (37) 1 рад = 1·10 <sup>-2</sup> дж/кг (37)
(41) Мощность поглощенной дозы излучения	СИ (7) СГС Внесистемная единица	(42) Ватт на килограмм (44) Эрг в секунду на грамм (46) рад в секунду	вт/кг (43) эрг (сек·г) (45) рад/сек (47)	— 1 эрг (сек·г) = 1·10 <sup>-4</sup> вт/кг (43) 1 рад/сек = 1·10 <sup>-2</sup> вт/кг (43)
(48) Экспозиционная доза γ-излучения	(1) СИ Внесистемная единица	(49) Кулон на килограмм (51) Рентген	(50) кг (52) р	(52) 1 р = 2,580·10 <sup>-4</sup> Кл/кг (воздуха) (50) (53)
(54) Мощность экспозиционной дозы γ-излучения	(1) СИ Внесистемная единица	(55) Ампер на килограмм (57) Рентген в секунду	(56) а/кг (58) р/сек	(58) 1 р/сек = 2,580·10 <sup>-4</sup> а/кг (56) (53) (всдуха)

Key: (1). Designation of values. (2). System of units. (3). Ones measurement. (4). Abbreviation. (5). Coefficient for bringing to SI units. (6). Activity of isotope in radioactive source. (7). SI extrasystemic unit. (8). Decay per second. (9). Curie. (10). disint./s. (11). curie. (12). Neutron flux or γ-quanta. (13). Neutron (γ-quanta) per square meter. (14). neutron/m<sup>2</sup>, γ/m<sup>2</sup>. (15). Neutron (γ-quanta) per square centimeter. (16). neutron/cm<sup>2</sup>, γ/cm<sup>2</sup>. (17). Only for neutron flux. (18). Neutron flux density or γ-quanta. (19). neutron(s·m<sup>2</sup>). (20). γ/(s·cm<sup>2</sup>). (21). Joule per square meter. (22). J/m<sup>2</sup>. (23). Ergs per square centimeter. (24). erg/cm<sup>2</sup>. (25). Electron

volt per square centimeter. (26).  $\text{eV}/\text{cm}^2$ . (27). Intensity of radiation/emission (energy current density). (28). Watts per square meter. (29).  $\text{W}/\text{m}^2$ . (30). No key. (31). Ergs per second to square centimeter. (32).  $\text{erg}/(\text{s}\cdot\text{cm}^2)$ . (33). Electron volt per second per square centimeter. (34).  $\text{eV}/(\text{s}\cdot\text{cm}^2)$ . (35). Absorbed radiation dosage. (36). Joule per kilogram. (37).  $\text{J}/\text{kg}$ . (38). Ergs to gram. (39).  $\text{erg}/\text{g}$ . (40). rad. (41). Power of absorbed radiation dosage. (42). Watts per kilogram. (43).  $\text{W}/\text{kg}$ . (44). Ergs per second to gram. (45).  $\text{erg}/(\text{s}\cdot\text{g})$ . (46). Rads per second. (47).  $\text{rad}/\text{s}$ . (48). Exposure dose of  $\gamma$ -radiation. (49). Coulomb per kilogram. (50).  $\text{C}/\text{kg}$ . (51). Roentgen. (52). r. (53). (air). (54). Power of exposure dose of  $\gamma$ -radiation. (55). Amperes per kilogram. (56).  $\text{A}/\text{kg}$ . (57). Roentgen per second. (58).  $\text{R}/\text{s}$ .

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